FAST DECOUPLED LOAD FLOW METHOD
IN RECTANGULAR COORDINATES

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CERTIFICATE

Certified that this work "FAST DECOUPLED LOAD FLOW METHOD I RECTANGULAR COORDINATES" by Laxmi Srivastava has been carried ou under our supervision and has not been submitted elsewhere fo the award of a degree.

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LIST OF PRINCIPAL SYMBOLS

n = number of buses in the system

δ_p, V_p = voltage angle, magnitude at bus p

δ_{pq} = $\delta_p - \delta_q$

e_p, f_p = real and imaginary components of the voltage

$V_p \angle\theta_p$ = $e_p + jf_p$ = complex bus voltage at the pth bus

Y_{pq} = $G_{pq} - jB_{pq}$ = 'pq' th element of bus admittance matrix

$P_{Gi} + jQ_{Gi}$ = real and reactive power generation at bus i

$P_{Li} + j_{QLi}$ = real and reactive power load at bus i

$P_i + jQ_i$ = net real and reactive power injections at bus i

The other symbols in the text are defined as when they are introduced.

ABSTRACT

Load flow study is very important for the purpose of planning, operation and control of power system both for off-line and on-line applications. During past four decades, extensive research efforts have been expended in the area of load flow studies. Amongst various load flow methods available, Newton based load flow methods as well as fast decoupled load flow techniques have been widely used by utilities. Newton-Raphson (NR) methods in polar as well as in rectangular co-ordinates are well known for offering reliable convergence to load flow solutions whereas fast decoupled load flow method in polar co-ordinates (FDLP), commercially developed, is known for less memory and CPU time requirements as compared to the two NR methods. Though, the convergence behaviour of these three methods are well established for well behaved systems, it was felt important to observe their performances for ill-conditioned situations as well. Hence, the motivation behind the work presented in this thesis, is to observe critically the relative performance of the two NR methods and the FDLP method in solving load flow problems for both well behaved as well as ill-conditioned cases in the systems.

Moreover, literature survey shows that very little attention have been paid to the development of FDLF method in rectangular co-ordinates. An attempt has, therefore, been made in the present

thesis to develop some new algorithms for fast decoupled load flow method in rectangular co-ordinates (FDLR) and to compare their relative peformances with the existing methods.

In the present work, computer programs have been developed to perform load flow studies by existing Newton-Raphson & fast decoupled load flow methods in polar as well as in rectangular co-ordinates and by the new FDLR algorithms. A comparative study of all these methods with reference to computation time, number of iterations and memory requirement for both normal and ill-conditioned situations in the system have been presented.

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CHAPTER - I

INTRODUCTION

1.1 General :-

The electrical power system is continuously expanding in size and growing in complexity all over the world. Extensive system studies on computers, both at off-line planning stage as well as at on-line operational stage, are therefore, a must. A power system engineer is always concerned with adopting newer and better mathematical models for solving system problems more efficiently and effectively. Load flow study is one such subproblem, which is so vital for almost all power system studies.

A large number of research efforts have been expended over the past four decades in the area of power flow (load flow) studies and yet there continues a constant and persistent search for better and still better solution algorithms for load flow study in terms of speed, memory and reliability aspects. This is due to the fact that the load flow study is of fundamental nature and any small improvement would be of considerable importance to the electric utilities and power companies.

The main objective of the work presented in this thesis is to carry out in-depth study on some existing load flow methods and to explore the possibility of developing new load flow algorithms.

Load flow study is a steady state solution of the power system problems which provides information about network power flows and bus voltages. Load flow studies on a digital computer essentially involves the solution of a set of non-linear algebraic equations.

During the past forty years, probably almost all the relevent known methods of numerical analysis for solving a set of non-linear algebraic equations have been applied in developing load flow algorithms. In addition, many methods based on some special features of the load flow equations have also been suggested. The most recurrent question arising in the load flow field is - which is the best method to choose for a given application? The answer is rarely easy. The relative properties and performance of different load flow methods can be influenced substantially by the type and the size of problem to be solved, by the computing facilities available and the precise details of implementation. The various desirable features of load flow methods can be :

- High speed, specially for real-time applications
- Low and compact storage, specially for small computers
- Reliability of convergence both for well-behaved and ill-conditioned systems
- Simplicity and ease of programming.

None of the methods available satisfy all the above criteria completely. Fortunately, not all the desirable features of load flow methods are essential in all the situations. A particular combination of the various features is needed in a given situation and hence, relentness effort continues to develop new load flow methods which would be more suitable for certain types of systems than the existing methods.

1.2 Literature Survey and Motivation :

With the enormous amount of literature available in the area of load flow study, it is not possible to present an exhaustive survey of all of them. Moreover, an excellent review paper by Stott [16] provides a detailed account of the load flow methods developed till 1974. Further, some of the common load flow algorithms are well documented in a number of books [25, 26, 27, 28, 29]. Hence, the survey attempted here mainly confines to brief and critical review of some of the important works and especially those relevent to the investigation carried out in this thesis.

Some of the earliest methods developed for load flow solution were based on successive displacement iteration schemes. Amongst them, the two nodal iterative methods [1,2] are based on bus admittance matrix [Y_{BUS}] formulation also popularly known as Gauss - iterative and Gauss - Seidel iterative methods. The attractive features of these methods are their simplicity and minimal storage - requirements. They are easily programmable and do not require a close estimate for initial bus voltages as is the case with most of the Newton based methods. However, these methods were slow in convergence and thus not very well suited to handle large systems.

The slow convergence of [Y_{BUS}] iterative method is mainly because of highly sparse nature of bus admittance matrix causing loose mathematical coupling between the buses. With this in view, load flow methods [3,5,8] based on bus matrix [Z_{BUS}] formulation were developed and found to take lesser number of iterations and were more reliable than the [Y_{BUS}] iterative models. However, the presence of P-V buses adversely affects their convergence behaviour. Further, because of increased computational time and storage requirements for computing and storing non-sparse [Z_{BUS}], the method did not gain widespread acceptance with the utilities.

An attempt was made by Freris and Sasson [9] to combine the desirable features of [Y_{BUS}] and [Z_{BUS}] iterative methods by having first few iterations by [Z_{BUS}] algorithm and switching over to [Y_{BUS}] algorithm for subsequent iterations. However, this method in general suffers from the same drawbacks as of pure [Z_{BUS}] model.

A number of algorithms based on the powerful Newton-Raphson (NR) method having quadratic convergence property have been proposed. The NR method essentially involves the linearization of the set of load flow equations at any iteration point using only the first order term in Taylor's series expansion. Several versions of NR method have been proposed and the popular ones are based on power mismatches. The power mismatch versions can be formulated using either the polar [6] or rectangular co-ordinates [4] for voltages. Some other versions are based on current mismatches [7]. The power mismatch version in polar co-ordinates has advantage over rectangular version in that it requires lesser memory space as number of variables are reduced. The current mismatch version works well only in lightly loaded systems. The power mismatch version in polar co-ordinates developed by Tinney and Hart [6] utilizes the sparsity exploitation and optimal ordering of buses and has been widely used by the utilities. This method usually converges to a fairly accurate solution in 4 to 5 iterations for most of the systems independent of their size and kind. Since, the convergence of the NR method is known to depend on good initial estimates of the variables otherwise there will be a large amount of truncation error, one or two iterations of Gauss-Seidel method or some other methods [12] may be used before applying NR method for load flow solution. Constant Jacobian version of the NR method [11,18] and some other modifications [13] have also been reported.

Some attempts have also been made to use minimization methods [10,20] for solving load flow problems. A minimization of sum of squares of current or power mismatches as objective function is considered whose global optimal coincides with the load flow solution. The minimization techniques used are gradient method [10], and linear programming method [20]. As concluded by Barras et al. [20], these methods are not competitive with NR algorithm for base case load flow application but are limited to contingency analysis.

Though N R load flow methods proved to be highly reliable, the storage requirement is considerable higher as compared to $[Y_{BUS}]$ Gauss-Seidel iterative methods. Decoupled versions of NR method [14,15] in polar form were attempted in view of reducing memory and computational time. In all these methods, the weak coupling between the active power-voltage magnitude and reactive power-voltage angles were exploited and two sets of linear equations, one to determine the corrections for voltage angles and the other to obtain the corrections for voltage magnitudes, were solved in each iteration. Amongst various decoupled versions fast decoupled load flow (FDLF) method developed by Stott an Alsac [15] is the most popular with utilities. The method is i polar co-ordinates and utilizes certain justifiable networ assumptions apart from the P-V and Q-δ decoupling to obtai constant Jacobian submatrices. The final model of FDLF is developed employing certain additional assumptions in computing elements of the submatrices [B'] and [B"]. The FDLF model developed is quite fast and reliable for a wide spectrum of systems. Wu [17] and Rao et al. [19] have tried to develop some empirical relations to study the convergence behaviour of FDLF method and have found it to exhibit poor convergence in certain cases of ill-conditioned systems. Nanda et al. [23] have examined the relative weightage and importance of various additional assumptions made by Stott and Alsac in their FDLF model on its convergence behaviour. Van Amerongen [24] suggested a different combination of considering additional assumptions in FDLF model which is more suitable for solving all types of systems.

From the literature survey presented, it is observed that Newton-Raphson [4,6] and fast decoupled [15] methods are the most popular ones for load flow solution. Newton Raphson (NR) methods in polar as well as rectangular co-ordinates are well known for offering reliable convergence to load flow solutions whereas fast decoupled load flow method in polar co-ordinates (FDLP) is known for less memory and C.P.U. time requirements as compared to the two NR methods. Though the convergence behaviour of these three methods are well established for well behaved systems, it was felt important to observe their behaviour for ill-conditioned situations in the systems. Hence, the motivation behind the works presented in this thesis was to observe critically the relative performances of the two NR methods and the FDLP method in solving load flow problems from the view point of memory requirements, number of iterations and C.P.U. time for both well behaved and ill-conditions situations in the systems.

Moreover, literature survey also shows that very little attention has been paid to the development of FDLF method in rectangular co-ordinates. Only two attempts seem to have been made by Arumugam [21] and Singh et al. [22] in this direction, which incidently results into similar formulations. An attempt has therefore also been made in the present thesis in the development of some new algorithms for fast decoupled load flow method in rectangular co-ordinates (FDLR) and compare their relative performances with the existing methods.

1.3 Outline of the Thesis :-

The chapter-wise summary of the works,covered out in this thesis is given as follows :-

Chapter-2 is devoted to the theoretical and numerical aspects of the NR method in rectangular co-ordinates (NRR) and also the NR method in polar co-ordinates (NRP). Both of these methods are tested on IEEE 14-Bus and 30-Bus test systems. A brief account of each method and their relative merits are also discussed in this chapter.

Chapter-3 deals with the fast decoupled load flow methods in polar as well as in rectangular co-ordinates. The two new algorithms for FDLR are also presented in this chapter. Potential of all these methods have been tested on IEEE 14-Bus and 30-Bus test systems both for well-behaved and ill-conditioned cases. The performances of various versions of fast decoupled load flow methods have been compared.

Finally, the Chapter-4 concludes the specific findings in this thesis along with future scope of the work.

CHAPTER - II

NEWTON BASED LOAD FLOW METHODS

2.1 Introduction :-

The objective of load flow study is to determine the voltage magnitude and its angle at each bus, real and reactive power flow in each line and line losses of the power system network for specified bus or terminal conditions. The mathematical model of the power system network for the purpose of load flow studies are a set of non-linear algebraic equations which can be solved by iterative techniques such as Gauss method, Gauss-Seidel method or Newton's method etc.

The Newton-Raphson's method is a powerful method of solving non-linear algebraic equations. It works faster, the number of iterations required to obtain solution is nearly independent of problem size and kind and is sure to converge in most cases as compared to the Gauss-Seidel (GS) method. In this chapter, Newton-Raphson's (NR) method in rectangular co-ordinates and also in polar co-ordinates for solving load flow problem are presented. The potential of both these Newton based methods for solving load flow problem have been critically examined for well behaved as well as ill-conditioned situations in the systems.

2.2 Load Flow Technique :

The load flow studies are conducted for the purpose of planning (viz. short, medium or long range planning), operation and control. For the purpose of load flow studies, we assume that the three phase power system network is balanced and we also neglect mutual coupling between elements. Variables associated with each bus of the power system include four quantities viz. voltage magnitude V, its phase angle δ, real power P and reactive power Q. Out of these four quantities, only two are generally specified at a bus and depending upon which two are specified, we have following three categories of buses :

a) Load or a P-Q Bus :

For this type of bus, we know apriori load values (P_{Li} and Q_{Li}) and specify the generations (P_{Gi} and Q_{Gi}). In fact we thus specify the bus injections P_i and Q_i. Solution of the load flow equations will render V_i and angle δ_i. A load bus which, due to its lack of generating equipment, is characterized by zero P_{Gi} and Q_{Gi} also falls in this category. Here P and Q are specified. Sometimes V limits are also specified.

b) P-V or a voltage controlled bus :

For this type of bus, we know apriori P_{Li} & Q_{Li} and specifyV_i and P_{Gi}. We thus specify P_i. Solutions of the load flow equations render Q_i (and hence Q_{Gi}) and angle δ_i. Such type of buses are also called a voltage controlled bus because its voltage can be controlled. Thus at P-V buses, real power P and voltage magnitude V are specified alongwith Q-limits to hold voltage within limits.

c) Slack or swing bus :

This is the reference bus where the voltage magnitude V and phase angle δ are specified. Voltage phase angle of such bus is normally specified as zero, thus it acts as reference to other bus voltage vectors. Usually a generator bus with maximum real power capability is selected as a slack bus. The variables of interest at this bus are the real and reactive powers. Generators at this bus is also required to supply additional real and reactive powers to meet the transmission losses which are unknown until the final load flow solution is obtained.

2.3 Newton-Raphson Method in Rectangular Coordinates :-

Assuming balanced 3-phase conditions as mentioned above, the transmission system network can be represented by its positive sequence network. The nodal admittance matrix $[Y_{bus}]$ which can be found by inspection, neglecting mutual coupling between elements,

can be expressed for a 'n' bus system as follows :

$$[\bar{I}_{bus}]_{nx1} = [Y_{bus}]_{nxn} \, [\bar{V}_{bus}]_{nx1} \quad \ldots\ldots\ldots\ldots\ldots (2.1)$$

The above equation can be written in the following form for the pth bus

$$\bar{I}_p = \sum_{q=1}^{n} (Y_{pq} \bar{V}_q) \quad \ldots\ldots\ldots\ldots\ldots\ldots (2.2)$$

where, p = 1,2,.............n.

This equation simply states that the current at any bus i the algebraic sum of all the currents entering or leaving the bus The power at any bus 'p' (P_p - jQ_p) is calculated using th relation :

$$P_p - jQ_p = \bar{V}_p^{*} I_p = \bar{V}_p^{*} \sum_{q=1}^{n} (Y_{pq} \bar{V}_q) \qquad (2.3)$$

In rectangular coordinates, we express

$$\bar{V}_p = e_p + jf_p$$

Where e_p and f_p are the real and imaginary components of the bus voltage at bus 'p' ($\bar{V}_p$)

$$Y_{pq} = G_{pq} - jB_{pq} \qquad (2.4)$$

Where G_{pq} and B_{pq} are conductance and susceptance part of the pqth element of $[Y_{BUS}]$ matrix respectively. Thus eqn. (2.3) can be rewritten as,

$$P_p - jQ_p = [e_p - jf_p] \sum_{q=1}^{n} [(G_{pq} - jB_{pq})(e_p + jf_q)] \qquad (2.5)$$

From eqn. (2.5), we determine the net injected real and reactive powers at bus p,

$$P_p = \text{Real } [\bar{V}_p^{*} \sum_{q=1}^{n} Y_{pq} . \bar{V}_q]$$

$$= \sum_{q=1}^{n} [e_p(e_q G_{pq} + f_q B_{pq}) + f_p(f_q G_{pq} - e_q B_{pq})] \qquad (2.6)$$

and

$$Q_p = \text{Imaginary } [\bar{V}_p^{*} \sum_{q=1}^{n} Y_{pq} \bar{V}_q]$$

$$= \sum_{q=1}^{n} [f_p(e_q G_{pq} + f_q B_{pq}) - e_p(f_q G_{pq} - e_q B_{pq})] \qquad (2.7)$$

Equations (2.6) and (2.7) at each bus form the load/power flow equations which involve four variables P, Q, e and f at each bus. Thus, for a n - bus system, total number of unknowns are 4n whereas the number of available equations are 2n only. Solution of these equations is obtained by specifying the values of two unknowns (out of four) at each bus and thus reducing the total number of unknowns to 2n only (equal to the number of equations to be solved). Variables, which are usually specified at various types of buses, are P and Q at load buses, e and f (or V and δ) at swing bus and P & V at generator buses, where at any bus 'p'

$$V_p^2 = e_p^2 + f_p^2 \qquad (2.8)$$

At a P-Q bus, since P and Q are specified, the mismatch vectors can be calculated as :

$$'_p = P_p^{sp} - P_p^{cal} \qquad (2.9)$$

$$\text{ʅ}_p = Q_p^{sp} - Q_p^{cal} \qquad (2.10)$$

For P-V bus, since P and V are specified, the mismatch vectors are calculated at any bus p using equation (2.9) and (2.11) given below

$$\Delta V_p^2 = (V_p^{sp})^2 - (V_p^{cal})^2 \qquad (2.11)$$

Where superscripts 'sp' and 'cal' stand for specified and calculated quantities respectively. P_p^{cal} and Q_p^{cal} are obtained from equations (2.6) and (2.7). V_p^{cal} is computed using equation (2.8).

Since load flow equations (2.6) and (2.7) are essentially non-linear algebraic equations, it can be solved by using any numerical technique. Solution of these equations using Newton-Raphson technique involves a linearized relationship between mismatch vector and voltage correction vector. For a n-bus system having bus-1 as slack bus, 2 to m as P-V buses and rest (m+1 to n) as load buses, the relationship between mismatch and correction vectors using NR method in rectangular co-ordinates, can be written as :

$$\left[\begin{array}{c} \Delta P_2 \\ \vdots \\ \Delta P_n \\ \hline \Delta V_2^2 \\ \vdots \\ \Delta V_m^2 \\ \hline \Delta Q_{m+1} \\ \vdots \\ \Delta Q_n \end{array}\right] = \left[\begin{array}{cccc} \frac{\partial P_2}{\partial e_2} & \frac{\partial P_2}{\partial e_n} & \frac{\partial P_2}{\partial f_2} & \frac{\partial P_2}{\partial f_n} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{\partial P_n}{\partial e_2} & \frac{\partial P_n}{\partial e_n} & \frac{\partial P_n}{\partial f_2} & \frac{\partial P_n}{\partial f_n} \\ \hline \frac{\partial V_2^2}{\partial e_2} & \frac{\partial V_2^2}{\partial e_n} & \frac{\partial V_2^2}{\partial f_2} & \frac{\partial V_2^2}{\partial f_n} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{\partial V_m^2}{\partial e_2} & \frac{\partial V_m^2}{\partial e_n} & \frac{\partial V_m^2}{\partial f_2} & \frac{\partial V_m^2}{\partial f_n} \\ \hline \frac{\partial Q_{m+1}}{\partial e_2} & \frac{\partial Q_{m+1}}{\partial e_n} & \frac{\partial Q_{m+1}}{\partial f_2} & \frac{\partial Q_{m+1}}{\partial f_n} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{\partial Q_n}{\partial e_2} & \frac{\partial Q_n}{\partial e_n} & \frac{\partial Q_n}{\partial f_2} & \frac{\partial Q_n}{\partial f_n} \end{array}\right] \left[\begin{array}{c} \Delta e_2 \\ \vdots \\ \Delta e_n \\ \hline \Delta f_2 \\ \vdots \\ \Delta f_m \\ \hline \Delta f_{m+1} \\ \vdots \\ \Delta f_n \end{array}\right] \tag{2.12}$$

The short, the above equation can be written as shown,

$$\left[\begin{array}{c} \Delta P \\ \hline \Delta V^2 \\ \hline \Delta Q \end{array}\right] = \left[\begin{array}{cc} J_1 & J_2 \\ \hline J_3 & J_4 \\ \hline J_5 & J_6 \end{array}\right] \left[\begin{array}{c} \Delta e \\ \Delta f \end{array}\right] \tag{2.13}$$

where, $\begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \\ J_5 & J_6 \end{bmatrix}$

is called the Jacobian matrix and $[\Delta e, \Delta f]^T$ form the voltage correction vector. J_1, J_2, J_3, J_4, J_5 and J_6 are Jacobian submatrices and their elements are defined as :

$(J_1)pq$ = Partial derivatives of P_p w.r.t. e_q's.
$(J_2)pq$ = Partial derivatives of P_p w.r.t. f_q's.
$(J_3)pq$ = Partial derivatives of V_p^2 w.r.t. e_q's.
$(J_4)pq$ = Partial derivatives of V_p^2 w.r.t. f_q's.
$(J_5)pq$ = Partial derivatives of Q_p w.r.t. e_q's.
$(J_6)pq$ = Partial derivatives of Q_p w.r.t. f_q's.

It can be shown, that, the off-diagonal elements of Jacobian submatrices (i.e. $q \neq p$) are as follows :

$$(J_1)pq = e_p G_{pq} - f_p B_{pq} \tag{2.14}$$

$$(J_2)pq = e_p B_{pq} + f_p G_{pq} \tag{2.15}$$

$$(J_3)pq = 0 \tag{2.16}$$

$$(J_4)pq = 0 \tag{2.17}$$

$$(J_5)pq = f_p G_{pq} + e_p B_{pq} \tag{2.18}$$

$$(J_6)pq = f_p B_{pq} - e_p G_{pq} \tag{2.19}$$

The diagonal elements of Jacobian submatrices (i.e. for $q = p$) are given as,

$$(J_1)pp = 2e_p G_{pp} + \sum_{\substack{q=1 \\ q \neq p}}^{n} [e_q G_{pq} + f_q B_{pq}] \tag{2.20}$$

$$(J_2)pp = 2f_p G_{pp} + \sum_{\substack{q=1 \\ q \neq p}}^{n} [f_q G_{pq} - e_q B_{pq}] \tag{2.21}$$

$$(J_3)pp = 2e_p \tag{2.22}$$

$$(J_4)pp = 2f_p \tag{2.23}$$

$$(J_5)pp = 2e_p B_{pp} - \sum_{\substack{q=1 \\ q \neq p}}^{n} [f_q G_{pq} - e_q B_{pq}] \tag{2.24}$$

$$(J_6)pp = 2f_p B_{pp} + \sum_{\substack{q=1 \\ q \neq p}}^{n} [e_q G_{pq} + f_q B_{pq}] \tag{2.25}$$

The solution of equation (2.13) gives us the Δe's and Δf's which are used to update earlier estimates of e's and f's and the process is repeated till the mismatch ΔP and ΔQ for P-Q buses and ΔP & ΔV^2 for P-V buses converge to a pre-assigned tolerance value ε.

2.3.1 Steps for Load Flow Solution using Newton-Raphson Method in Rectangular Coordinates :

The procedure for solving the load flow problem using Newton Raphson method in rectangular co-ordinates is described through flow chart given fig. (2.1). Major computational steps are as given below :

1. Read system data including line data, loads at various buses, generator data.
2. Form $[Y_{BUS}]$ matrix.
3. Initialize the voltage at each bus. If nothing is prespecified, assume a flat start $(1 + j0)$ i.e. assign V at all buses equal to 1.0 p.u. and angle δ equal to slack bus angle i.e. zero. Set iteration count $k = 0$.
4. Calculate P^{cal} and Q^{cal} using equations (2.6) and (2.7) with available values of e's and f's for P-Q buses.
5. Calculate P^{cal}, and voltage magnitude using eqns. (2.6) and (2.8) with avaialble values of e's and f's for P-V buses.
6. Calculate power mismatch ΔP for all P-Q and P-V buses and ΔQ for all P-Q buses using equations (2.9) and (2.10) respectively.
7. For P-V buses, check if Q^{cal} is within the specified Q limits $(Q^{min} \leq Q^{cal} \leq Q^{max})$. If it is so, calculate ΔV^2 using eqn. (2.11). But if Q^{cal} is less than Q^{min} or greater than Q^{max}, we proceed as follows :

if $Q^{cal} > Q^{max}$,

substitute $Q^{cal} = Q^{max}$

if $Q^{cal} < Q^{min}$,

substitute $Q^{cal} = Q^{min}$

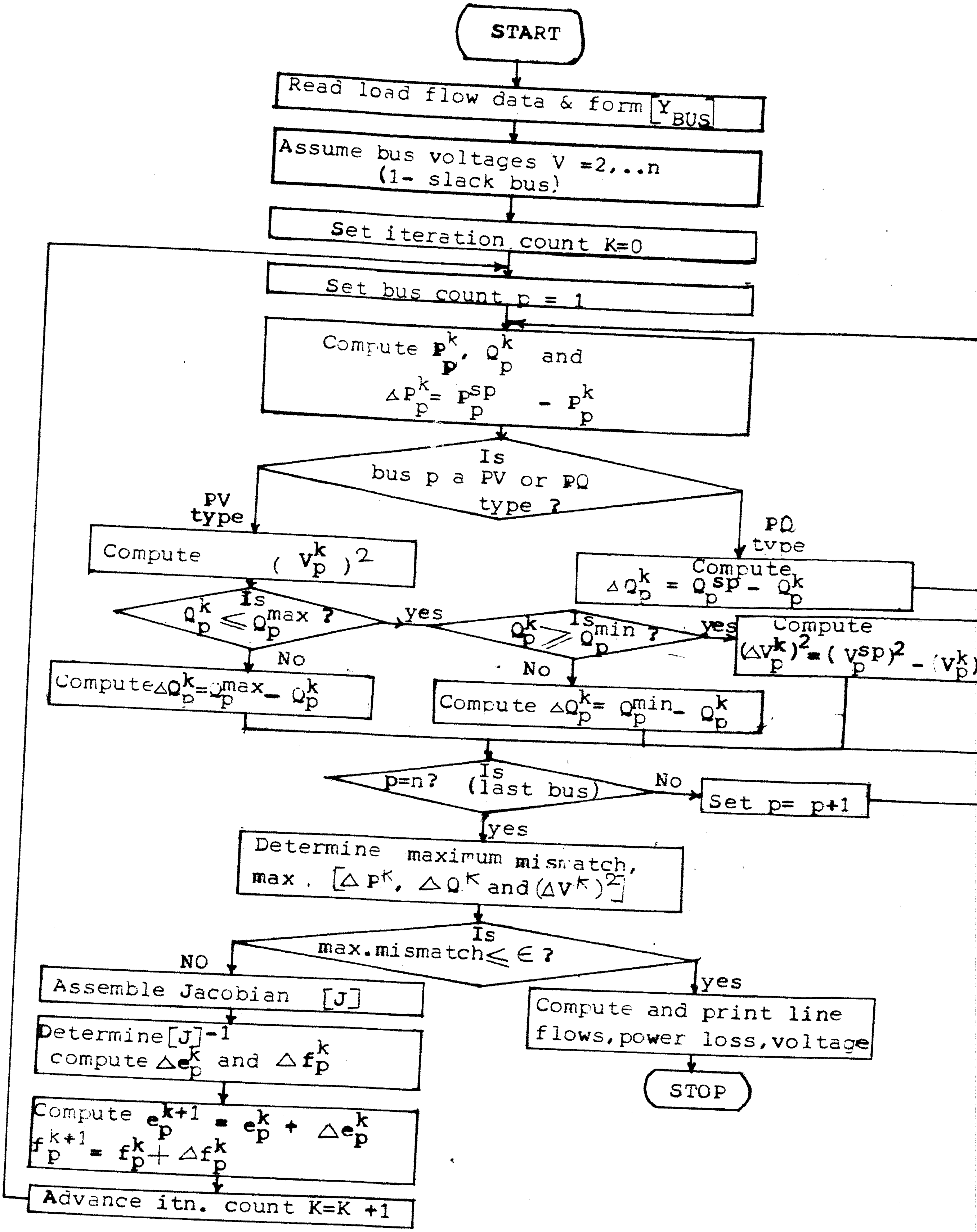
START
Read load flow data & form [Y_BUS]
Assume bus voltages V =2,..n
(1- slack bus)
Set iteration count K=0
Set bus count p = 1
Compute P_p^k, Q_p^k and
$\Delta P_p^k = P_p^{sp} - P_p^k$
Is bus p a PV or PQ type ?
PV type
PQ type
Compute $(V_p^k)^2$
Compute $\Delta Q_p^k = Q_p^{sp} - Q_p^k$
Is $Q_p^k \leqslant Q_p^{max}$?
yes
No
Is $Q_p^k \geqslant Q_p^{min}$?
yes
No
Compute $(\Delta V_p^k)^2 = (V_p^{sp})^2 - (V_p^k)$
Compute $\Delta Q_p^k = Q_p^{max} - Q_p^k$
Compute $\Delta Q_p^k = Q_p^{min} - Q_p^k$
Is p=n? (last bus)
No
Set p= p+1
yes
Determine maximum mismatch, max . $[\Delta P^k, \Delta Q^k$ and $(\Delta V^k)^2]$
Is max.mismatch $\leqslant \in$?
NO
yes
Assemble Jacobian [J]
Determine $[J]^{-1}$
compute Δe_p^k and Δf_p^k
Compute $e_p^{k+1} = e_p^k + \Delta e_p^k$
$f_p^{k+1} = f_p^k + \Delta f_p^k$
Advance itn. count K=K +1
Compute and print line flows, power loss, voltage
STOP

Fig. 2.1 Flow chart for Newton-Raphson method in Rectangular co-ordinates.

and treat this bus as a P-Q bus. Reactive power mismatch ΔQ is found using eqn. (2.10).

8. If ΔP and ΔQ at all P-Q buses and ΔP and ΔV^2 at all P-V buses are less than a pre-specified tolerence ε, go to step-13, otherwise go to step-9.

9. Calculate the elements of Jacobian using equations (2.14) through (2.25) and find the inverse of Jacobian matrix.

10 Solve equation (2.13) for voltage mismatch vectors Δe and Δf.

11. The assumed or calculated bus voltage components e and f are updated at all the buses using the correction vector obtained, as follows

$$e^{(k+1)} = e^k + \Delta e^k \tag{2.26}$$

$$f^{(k+1)} = f^k + \Delta f^k \tag{2.27}$$

where, e^k and f^k are the values of voltages at the kth iteration.

12. Advance the iteration count by '1' (k = k+1) and go to step-4.

13. Load flow convergence obtained, calculate slack bus power, line flows and line losses etc.

2.4 Newton-Raphson Method in Polar Coordinates :

The load flow problem using Newton-Raphson method in polar coordinates (NRP) can be formulated as follows. For any bus-p, we have

$$\bar{V}_p = V_p\, e^{j\delta p}, \text{ then } \bar{V}^{*}_p = V_p e^{-j\delta p}$$

$$\bar{V}_q = V_q\, e^{j\delta q}, \; Y_{pq} = |Y_{pq}| e^{-j\theta pq} \qquad (2.28)$$

where δ is the angle of the bus voltage and θpq is bus admittance angle. Then for any bus p,

$$P_p - jQ_p = \bar{V}^{*}_p \sum_{q=1}^{n} (Y_{pq}\, \bar{V}_q) \qquad (2.29)$$

Substituting relations (2.28) in eqn. (2.29) we get

$$P_p - jQ_p = \sum_{q=1}^{n} [\, V_p |Y_{pq}| V_q \; e^{-j(\theta_{pq} + \delta_p - \delta_q)}] \qquad (2.30)$$

Thus

$$P_p = \text{Real} \left[\sum_{q=1}^{n} V_p |Y_{pq}| V_q \; e^{-j(\theta_{pq} + \delta_p - \delta_q)} \right]$$

$$= \sum_{q=1}^{n} [\, V_p |Y_{pq}| V_q \;\; \text{Cos}\, (\theta_{pq} + \delta_p - \delta_q)]$$

$$= \sum_{q=1}^{n} V_p \;\; V_q \;\; [G_{pq} \;\text{Cos}(\delta_p - \delta_q) + B_{pq} \;\text{Sin}(\delta_p - \delta_q)] \qquad (2.31)$$

$$\text{and } \; Q_p = \text{Imaginary} \left[\sum_{q=1}^{n} V_p |Y_{pq}| V_q \;\; e^{-j(\theta_{pq} + \delta_p - \delta_q)} \right]$$

$$= \sum_{q=1}^{n} [\, V_p \;\; V_q |Y_{pq}| \;\; \text{Sin}(\theta_{pq} + \delta_p - \delta_q)]$$

$$= \sum_{q=1}^{n} V_p \; V_q \; [G_{pq} \; \mathrm{Sin}(\delta_p - \delta_q) - B_{pq} \; \mathrm{Cos}(\delta_p - \delta_q)] \qquad (2.32)$$

Equation (2.31) and (2.32) form the pair of load flow equations at each bus in the system. The solution of load flow equations in polar coordinates involve real power mismatch (ΔP) at P-Q as well as at P-V buses and reactive power mismatch (ΔQ) at only P-Q buses. At any bus -p, these can be calculated as,

$$\Delta P = P_p^{sp} - P_p^{cal}$$

$$\Delta Q = Q_p^{sp} - Q_p^{cal}$$

P_p^{cal} and Q_p^{cal} are obtained using eqns. (2.31) and (2.32). For calculated values of mismatch vector, the voltage corrections ΔV and $\Delta\delta$ can be computed using NR relation in polar coordinates as shown,

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} \qquad (2.33)$$

where, $\begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix}$

is called the Jacobian matrix. J_1, J_2, J_3 and J_4 are Jacobian submatrices whose elements are defined as :

$(J_1)pq$ - Partial derivatives of P_p w.r.t. δ_q's.

$(J_2)pq$ - Partial derivatives of P_p w.r.t. V_q's.

$(J_3)pq$ - Partial derivatives of Q_p w.r.t. δ_q's.

$(J_4)pq$ - Partial derivatives of Q_p w.r.t. V_q's.

For a n-bus system having (m-1) P-V buses, the size of Jacobian matrix is (2n-m-1) x (2n-m-1).

It can be shown, that, the off-diagonal elements of Jacobian submatrices (i.e. for $q \neq p$) are,

$$(J_1)pq = V_p V_q [G_{pq} \operatorname{Sin}(\delta_p - \delta_q) - B_{pq} \operatorname{Cos}(\delta_p - \delta_q)] \tag{2.34}$$

$$(J_2)pq = V_p [G_{pq} \operatorname{Cos}(\delta_p - \delta_q) + B_{pq} \operatorname{Sin}(\delta_p - \delta_q)] \tag{2.35}$$

$$(J_3)pq = -V_p V_q [G_{pq} \operatorname{Cos}(\delta_p - \delta_q) + B_{pq} \operatorname{Sin}(\delta_p - \delta_q)] \tag{2.36}$$

$$(J_4)pq = V_p [G_{pq} \operatorname{Sin}(\delta_p - \delta_q) - B_{pq} \operatorname{Cos}(\delta_p - \delta_q)] \tag{2.37}$$

The diagonal elements of Jacobian submatrices (i.e. for q = p) are

$$(J_1)pp = \sum_{\substack{q=1 \\ q \neq p}}^{n} V_p V_q [B_{pq} \operatorname{Cos}(\delta_p - \delta_q) - G_{pq} \operatorname{Sin}(\delta_p - \delta_q)] \tag{2.38}$$

$$(J_2)pp = 2\, V_p \quad G_{pp} + \sum_{\substack{q=1 \\ q \neq p}}^{n} V_q \, [G_{pq} \operatorname{Cos}(\delta_p - \delta_q) + B_{pq} \operatorname{Sin}(\delta_p - \delta_q)] \tag{2.39}$$

$$(J_3)pp = \sum_{\substack{q=1 \\ q\neq p}}^{n} V_p \; V_q \; [G_{pq} \; Cos(\delta_p - \delta_q)+B_{pq} \; Sin(\delta_p-\delta_q)] \quad (2.40)$$

$$(J_4)pp = -2 \; V_p \; B_{pp} + \sum_{\substack{q=1 \\ q\neq p}}^{n} V_q \; [G_{pq} \; Sin(\delta_p-\delta_q)-B_{pq} \; Cos(\delta_p-\delta_q) \;] \quad (2.41)$$

The solution of eqn. (2.33) gives us the $\Delta\delta$'s and ΔV's which are used to update, the earlier estimates of δ's and V's and the process is repeated till the mismatch ΔP for all P-V and P-Q buses and ΔQ for all P-Q buses become less than a pre-assigned tolerance value ε.

2.4.1 Steps for Load Flow Solution using Newton-Raphson Method in Polar Coordinates

Flow chart given in fig. (2.2) describes the procedure for solving load flow problem using Newton-Raphson method in polar coordinates. However, major computational steps are as given below :

1. Read system data including line data, loads at various buses, generator data.
2. Form $[Y_{BUS}]$ matrix.
3. Initialize the voltage at each bus. If nothing is prespecified, assume a flat start i.e. assign V at all buses equal to 1.0 p.u. and angle equal to slack bus angle i.e. zero. Set iteration count k = 0.

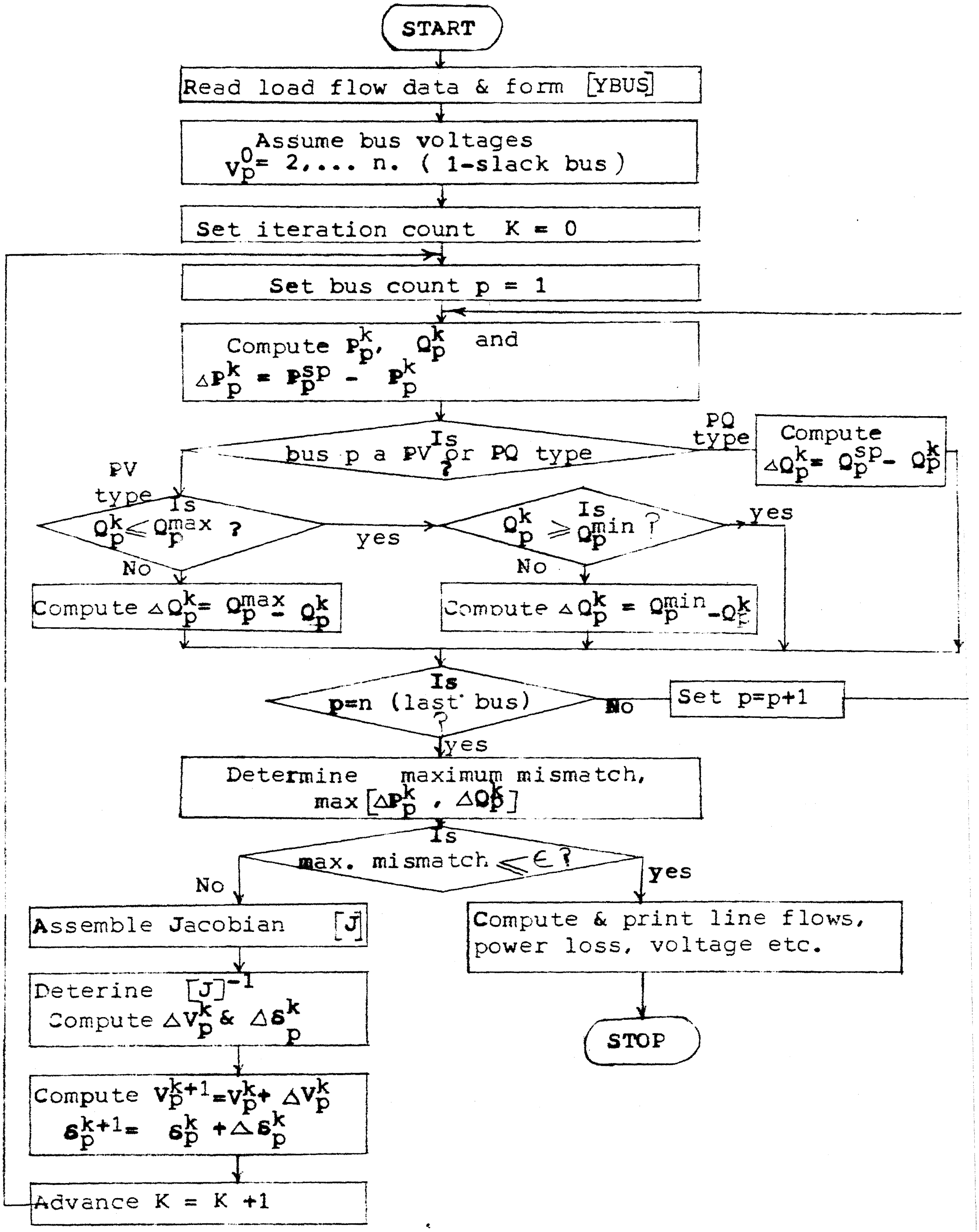
START
Read load flow data & form [YBUS]
Assume bus voltages V_p^0= 2,... n. (1-slack bus)
Set iteration count K = 0
Set bus count p = 1
Compute P_p^k, Q_p^k and $\Delta P_p^k = P_p^{sp} - P_p^k$
Is bus p a PV or PQ type ?
PV type
PQ type
Compute $\Delta Q_p^k = Q_p^{sp} - Q_p^k$
Is $Q_p^k \leq Q_p^{max}$?
yes
No
Is $Q_p^k \geq Q_p^{min}$?
yes
No
Compute $\Delta Q_p^k = Q_p^{max} - Q_p^k$
Compute $\Delta Q_p^k = Q_p^{min} - Q_p^k$
Is p=n (last bus) ?
No
Set p=p+1
yes
Determine maximum mismatch, max $[\Delta P_p^k , \Delta Q_p^k]$
Is max. mismatch $\leq \epsilon$?
No
yes
Assemble Jacobian [J]
Deterine $[J]^{-1}$ Compute ΔV_p^k & $\Delta \delta_p^k$
Compute $V_p^{k+1} = V_p^k + \Delta V_p^k$ $\delta_p^{k+1} = \delta_p^k + \Delta \delta_p^k$
Advance K = K +1
Compute & print line flows, power loss, voltage etc.
STOP

Fig- 2.2 Flow chart for Newton-Raphson method in polar co-ordinates.

4. Calculate P^{cal} and Q^{cal} using equations (2.31) and (2.32) with available values of V's and δ's.

5. For P-V buses replace temporarily V^k by V^{sp} but leave δ^k as it is. Compute Q^{cal} for P-V bus using V^{sp}.

6. For P-V buses, check if Q^{cal} is within the specified Q limits (i.e. $Q^{min} \le Q^{cal} \le Q^{max}$). If it is so, put of $V^k = V^{sp}$, and calculate ΔP only using eqn. (2.9). But if Q^{cal} hits the Q limit, proceed as follows :

$$\begin{array}{llll} \text{if} & Q^{cal} & > & Q^{max} \\ \text{put} & Q^{cal} & = & Q^{max} \\ \text{if} & Q^{cal} & < & Q^{min} \\ \text{put} & Q^{cal} & = & Q^{min} \end{array}$$

and treat this bus as P-Q bus. Use V^k as it is and find power mismatch ΔP and ΔQ using eqns. (2.9) and (2.10) for all P-Q buses.

7. If ΔP's and ΔQ's at all P-Q buses and ΔP's for all P-V buses are less than a pre-specified tolerance go to step-12, otherwise go to step-8.

8. Calculate the elements of Jacobian using eqns. (2.34) through (2.41) and find the inverse of Jacobian matrix.

9. Solve eqn. (2.33) for voltage correction vector ΔV and $\Delta\delta$.

10. The assumed or calculated voltage magnitudes and their angles are updated using the correction vector obtained as follows :

$$\delta^{(k+1)} = \delta^k + \Delta\delta^k \qquad (2.42)$$

$$V^{(k+1)} = V^k + \Delta V^k \qquad (2.43)$$

where, δ^k and V^k are the values at kth iteration.

11. Advance the iteration count by '1' (k = k+1) and go to step-4.
12. Load flow convergence obtained, calculate slack bus power, line flows and line losses.

2.5 Sample System Studies :

The Newton-Raphson method outlined in section 2.3 and 2.4 have been tested by solving the load flows for the following sample power systems using DEC-1090 computer.

1. IEEE - 14 bus test system.
2. IEEE - 30 bus test system.

The specification of the above systems are given in Appendices A & B.

A convergence critierion of 0.0001 p.u. for active and reactive power mismatches and for voltage magnitude square mismatches has been taken on a 100 MVA base. The results have been obtained for both well behaved and ill-conditioned cases. Ill-conditioning in the system has been created by raising the series resistance of all the lines simultaneously from their base values (Increased R/X ratio). Load flow solutions on these systems using the flat voltage start are listed in Tables 2.1 to 2.3. The number of iterations and total C.P.U. time for load flow solution is shown in Table 2.1. Tables 2.1 and 2.2 pertain to unadjusted solution (no Q-limits imposed), whereas Table 2.3 corresponds to adjusted solutions considering the generator Q-limits. Table 2.2 compares the convergence characteristics for ill-conditioned situation. Cases for increased R/X ratio of lines have been shown as $[(1+\alpha)R + jX]$ in Table 2.2 which indicates that the series resistances of all the lines are increased by 'α' times their base values.

The convergence pattern of both NRR and NRP methods have been studied by plotting the values of power mismatches obtained in each iteration for the study of unadjusted base case and are shown in figures (2.3) and (2.4). Analysis of these figures clearly reveal the quadratic convergence pattern of load flow solution using either NRR or NRP method. It is also seen that with the increase in number of buses, the NRP seems to be better than that of NRR as for as CPU time is concerned. However the number of iteration required in both these methods are same and do not vary much with the increase in problem size and kind.

TABLE - 2.1

Comparison of NRR and NRP methods for load flow solution (unadjusted case)

Method	I E E E - 14 BUS SYSTEM		I E E E - 30 BUS SYSTEM	
	No. of Iteration	Total C.P.U. Time (seconds)	No. of Iteration	Total C.P.U. Time (seconds)
NRR	3	2.085	3	15.564
NRP	3	2.631	3	18.071

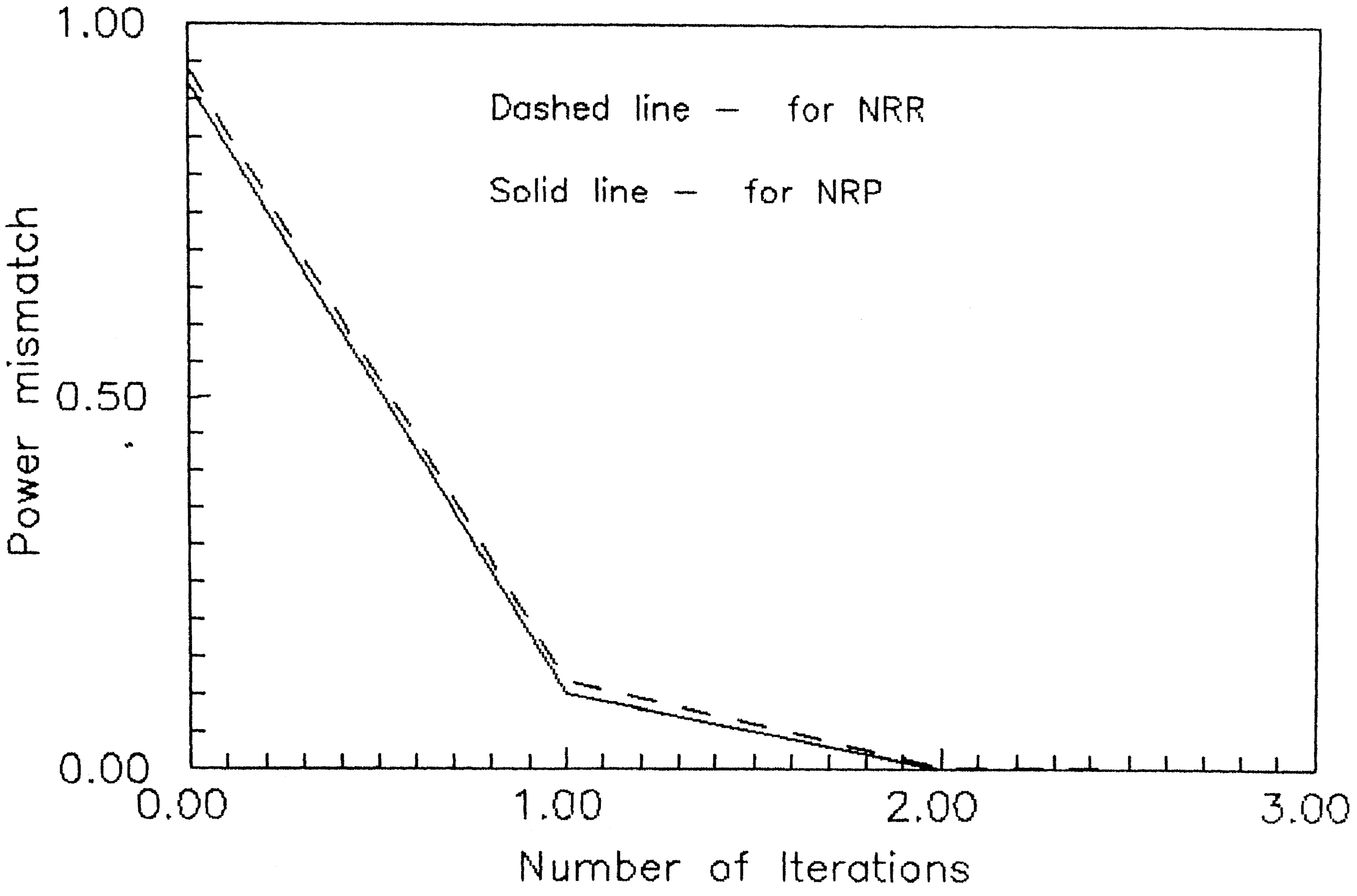

FIG — 2.3 Convergence of Newton Raphson method in rectangular & polar co-ordinates. (IEEE — 14 Bus System)

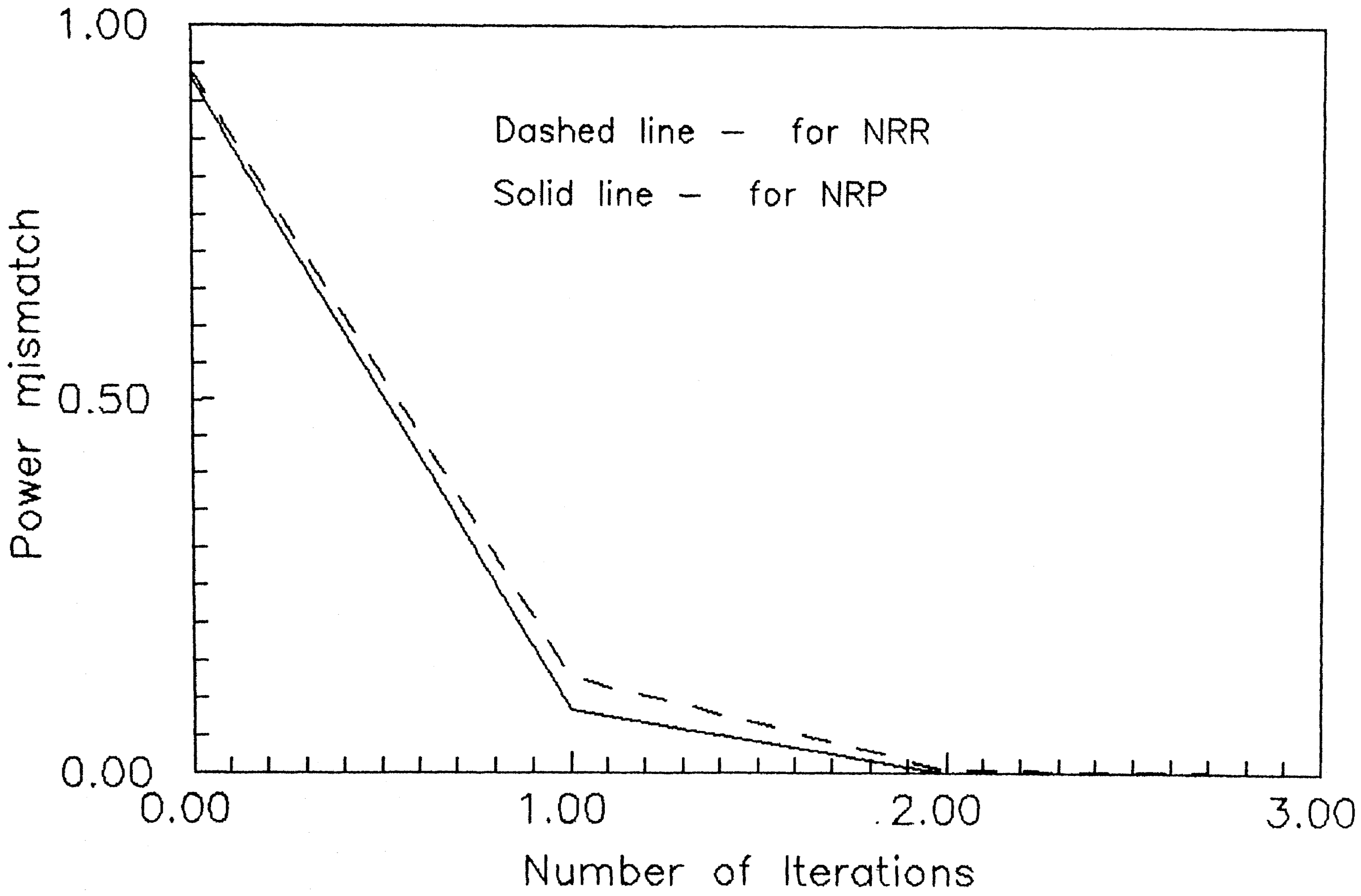

FIG – 2.4 Convergence of Newton Raphson method in rectangular & Polar co–ordinates (IEEE – 30 Bus System)

TABLE - 2.2

Effect of Large R/X Ratio on Convergence

Ill-conditioning case	No. of Iterations IEEE -14 BUS SYSTEM		No. of Iterations IEEE -30 BUS SYSTEM	
$(1+\alpha)R+jX$	NRR	NRP	NRR	NRP
2R+jX	3	3	3	3
3R+jX	4	3	4	3
4R+jX	4	4	6	5

TABLE - 2.3

Comparison of NRR and NRP methods for adjusted case (Q-Limits)

Method	IEEE - 14 BUS SYSTEM		IEEE - 30 BUS SYSTEM	
	No. of Iteration	Total C.P.U. Time (seconds)	No. of Iteration	Total C.P.U. Time (seconds)
NRR	6	3.987	7	35.537
NRP	7	5.756	7	40.854

2.6 Discussion and Conclusion :

From the result shown in above tables, it is clear that NRR is slightly faster than NRP. Number of iterations required in both cases are almost the same. However number of equations and variables in NR method in rectangular coordinates is greater than that in NRP, by the number of P-V buses. Hence memory requirement in NRR is more than that in NRP. Computation time in rectangular coordinates (NRR) is less because time consuming trigonometrical functions are not present. Thus, the formulation in rectangular coordinates takes less computational effort and that in polar-coordinates takes less memory space. Though the number of iterations required to obtain load flow solution using either of the methods is almost independent of problem size and kind.

Newton's methods are also unaffected by ill-conditioned situations viz. negative transfer reactances which can not be netted with positive reactance of the line and a situation where high and low impedance branch terminate at the same node. The NR method needs 4 to 5 iterations to reach an acceptable solution for a large system. However, the time per iteration in both these methods (NRR and NRP) increase almost directly as the number of buses of the network. If Q-limits are considered, the NR method takes more iterations than that for unadjusted solution.

Since, the NR method requires number of iterations independent of problem size and kind, it is more advantageous for large scale systems. NR method has quadratic convergence characteristics and is the best among all methods from the stand point of convergence criterion. With NR method, the elements of the Jacobian are to be computed in each iteration, and hence, the time per iteration is considerably longer than Gauss-Seidel method (about 7 times). In fact, the NR method is more reliable and is able to solve a wider variety of problems. Its main drawback of the large requirement of computer memory can be over-come by a compact storage scheme. It can be made faster by adopting the scheme of optimally ordering of buses etc. Further in NR method it is necessary that the initial guess is not far off from the nominal solution otherwise there will be quite a large truncation error.

CHAPTER - III

FAST DECOUPLED LOAD FLOW METHODS

3.1 Introduction :

Amongst the various load flow methods available, the fast decoupled load flow method is the most popular with utilities for obtaining load flow solution because of its reduced memory requirements and providing faster solution. The FDLF method is attractive for accurate as well as for approximate off- and on-line routine and contingency calculations for networks of any size and kind. In this chapter, the fast decoupled load flow (FDLF) method of Stott and Alsoc [15] in polar coordinates and existing FDLF method in rectangular coordinates [21,22] are discussed. New FDLF algorithms in rectangular coordinates considering certain modifications in the existing one is also presented in this chapter, which is found to provide convergence especially for ill-conditioned situations in the system. Various existing and new models of FDLF method have been tested on I.E.E.E. 14-bus and 30-bus systems and their performances compared for well-behaved and ill-conditioned cases in the systems.

3.2 Newton-Raphson Decoupled Load Flow Model

Newton-Raphson load flow method developed by Tinney and Hart [6]at B.P.A. Portland (ORE-USA) is one of the most powerful methods. The number of iterations required to obtain solution by this method is independent of problem size and kind. Even with flat voltage start, it takes nearly 4 to 5 iterations to obtain the solution, even though the time taken to complete one iteration is nearly seven times to that of the Gauss-Seidel method, still this method is faster for large scale systems. This method is not affected by ill-conditioned situations and also with slight modifications, all the other factors such as representation of transformers etc. can be included in the same Jacobian.

The load flow equations used in this method for computation of voltage corrections are given as,

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} H & N \\ J & L \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \frac{\Delta V}{V} \end{bmatrix} \qquad (3.1)$$

where,

$$H_{km} = \frac{\partial P_k}{\partial \delta_m} \quad ; \quad N_{km} = \frac{\partial P_k V_m}{\partial V_m}$$

$$J_{km} = \frac{\partial Q_k}{\partial \delta_m} \quad ; \quad L_{km} = \frac{\partial Q_k V_m}{\partial V_m}$$

H, N, J and L are the submatrices of the Jacobian.

The decoupled method [14] is actually an extension of Newton's method in polar coordinates eqn. (3.1) with certain approximations. Since the changes in real power (i.e. ΔP) is less sensitive to the change in voltage magnitude (i.e. ΔV) and changes in reactive power ΔQ is less sensitive to the changes in angle $\Delta\delta$, we can write the eqn. (3.1) in the following form,

$$\begin{bmatrix} \Delta P \\ \\ \Delta Q \end{bmatrix} = \begin{bmatrix} H & O \\ \\ O & L \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \\ \dfrac{\Delta V}{V} \end{bmatrix} \qquad (3.2)$$

Equations (3.2) are decoupled equations which can be expanded as

$$[\Delta P] = [H] \quad [\Delta \delta] \qquad (3.3)$$

$$[\Delta Q] = [L] \begin{bmatrix} \dfrac{\Delta V}{V} \end{bmatrix} \qquad (3.4)$$

It can be shown that the off-diagonal elements of Jacobian (i.e. for $q \neq p$) are,

$$H_{pq} = L_{pq} = V_p \, V_q \, [G_{pq} \, \mathrm{Sin}(\delta_p - \delta_q) - B_{pq} \, \mathrm{Cos}(\delta_p - \delta_q)] \qquad (3.5)$$

The diagonal elements of [H] and [L] are

$$H_{pp} = - V_p^2 \, B_{pp} - Q_p \qquad (3.6)$$

$$L_{pp} = - V_p^2 \, B_{pp} + Q_p \qquad (3.7)$$

Equations (3.3) and (3.4) are formulated and solved successively. The latest values of δ found from eqn. (3.3) are used to solve for eqn. (3.4). The decoupled method converges as reliably as the full Newton-Raphson method, although it takes more number of iterations as compared to the Newton's method. The saving in terms of memory requirements is about 75% for Jacobian elements although overall saving of the memory is only of the order of 40-50%. The computation time per iteration is also 10-20% less than full Newton-Raphson method.

3.3 Fast Decoupled Load Flow Method in Polar Co-ordinates :

The decoupled method [14] can be further simplified without appreciable loss of accuracy. In practical power system, the following assumptions hold good :

1. $(\delta_p - \delta_q)$ is small.
2. $G_{pq} \; \mathrm{Sin}(\delta_p - \delta_q) << B_{pq}$.
3. $Q_p << B_{pp} . V_p^2$.

Applying these assumptions to equations (3.3) and (3.4), we get

$$[\Delta P] = [V.B'.V] \, [\Delta\delta] \tag{3.8}$$

$$[\Delta Q] = [V.B''.\ V] \left[\frac{\Delta V}{V} \right] \tag{3.9}$$

The elements of the matrices [B'] and [B"] used in eqns. (3.8) and (3.9) are directly derived from elements of [-B]. The decoupling process is given a final form by following additional assumptions :

a) Omitting from [B'] the representation of those network elements that affects MVAR flows i.e. shunt reactances and off-nominal in-phase transformer taps.

b) Omitting from [B"], the angle shifting effects of phase shifters.

c) Neglecting series resistances in calculating the elements of [B'] and dividing eqns. (3.8) and (3.9) by V_p when calculating for pth bus, and setting $V_q = 1$ p.u.

With these assumptions, equations (3.8) and (3.9) take the following form

$$\left[\frac{\Delta P}{V}\right] = [B'] \, [\Delta\delta] \tag{3.10}$$

$$\left[\frac{\Delta Q}{V}\right] = [B''] \, [\Delta V] \tag{3.11}$$

which are the set of equations used in fast decoupled load flow model [15] in polar co-ordinates.

In eqns. (3.10) and (3.11) [B'] and [B"] matrices are real, sparse and have the structure of [H] and [L] respectively. Since they contain only network admittances, they are constant and need to be triangulated once only at the beginning of the iteration. Using the constant triangular factors of [B'] and [B"], very fast repeat solutions for [$\Delta\delta$] and [ΔV] are obtained. The best scheme for FDLP is to solve eqns. (3.10) and (3.11) alternately, always using the most recent voltage values. Each iteration cycle comprises one solution for [$\Delta\delta$] to update [δ] and then one solution for [ΔV] to update [V], and termed as (1-δ, 1-V) scheme. The iterative procedure is repeated till the real and reactive power mismatches become less than a pre-assigned tolerance value

(ε). Various storage schemes can be applied to take the advantage of sparsity and symmetry of [B'] and [B"]. However, [B'] is symmetrical only if the phase-shifters are neglected.

3.3.1 Steps for the FDLP iteration scheme :

Major computational steps for solving load flow problem using FDLP method are shown in a flow chart (fig. 3.1) which are summarized as follows :

1) Read system data including line data, loads at various buses, generation data etc.
2) Form Y-bus matrix, [B'] and [B"] matrices.
3) Initialize the bus voltage to (1+j0) p.u. for all P-Q buses and (V^{sp} + j0) for all P-V type buses.
4) Set iteration count k = 0.
5) Calculate bus real power P and mismatch ΔP for all buses except slack bus using

$$\Delta P = P^{sp} - P^{cal} \tag{3.12}$$

6) Check, if real power has converged to its specified values (Max. ΔP ≤ ε). If so, go to step (9), otherwise go to step-7.
7) Advance iteration count by 0.5 (k = k + 0.5) and solve for Δδ using eqn. (3.10).
8) Update the voltage angle δ at all buses (except slack bus) using the corrections Δδ obtained in step-7

$$\delta = \delta + \Delta\delta \tag{3.13}$$

9) Calculate bus reactive power Q and mismatch ΔQ for all P-Q buses using following eqn.

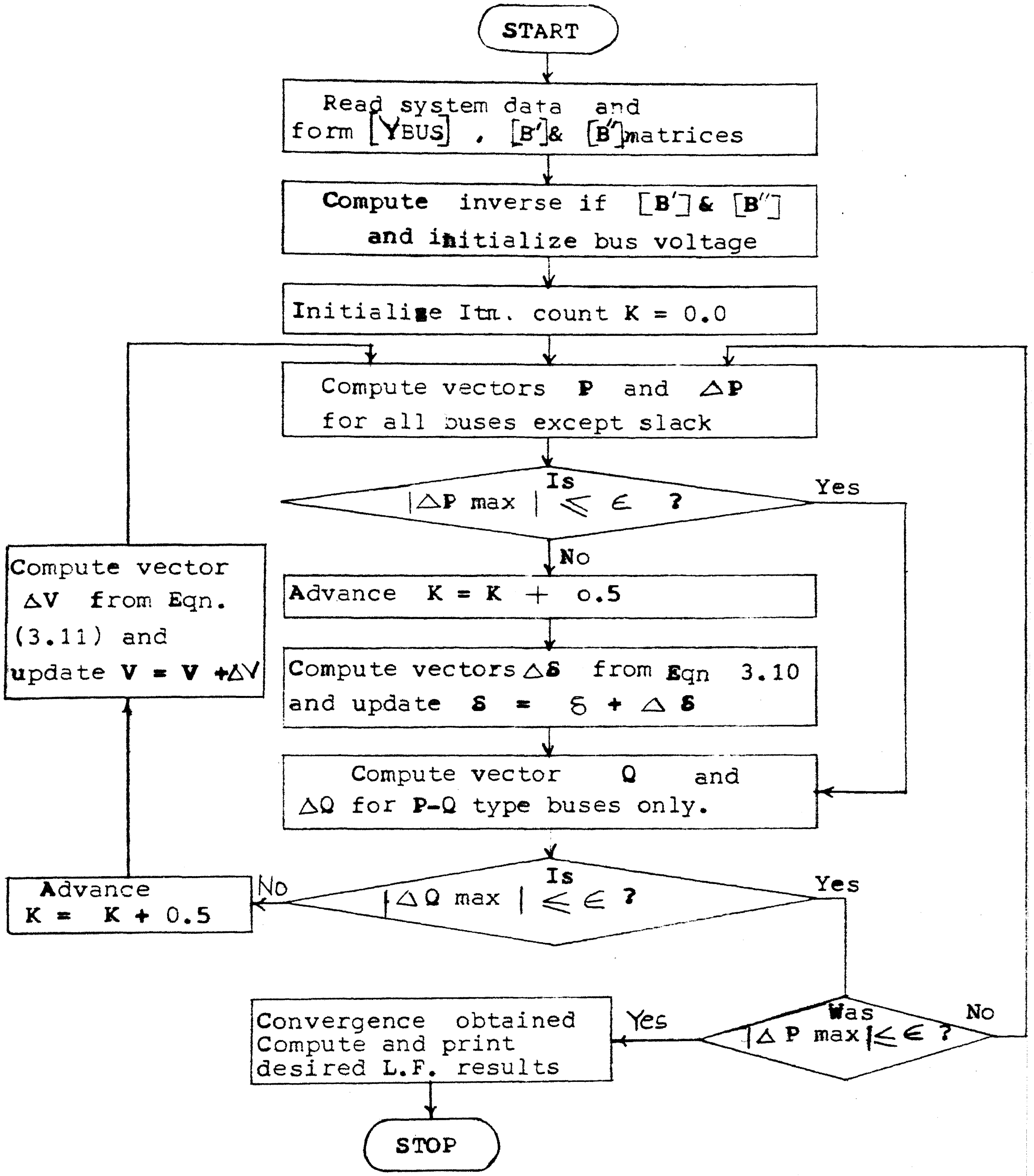
START
Read system data and form [YBUS] , [B′]& [B″]matrices
Compute inverse if [B′]& [B″] and initialize bus voltage
Initialize Itn. count K = 0.0
Compute vectors P and ΔP for all buses except slack
Is |ΔP max| ≤ ∈ ?
Yes
No
Advance K = K + 0.5
Compute vectors Δδ from Eqn 3.10 and update δ = δ + Δ δ
Compute vector Q and ΔQ for P-Q type buses only.
Is |ΔQ max| ≤ ∈ ?
Yes
No
Advance K = K + 0.5
Compute vector ΔV from Eqn. (3.11) and update V = V +ΔV
Was |Δ P max|≤ ∈ ?
Yes
No
Convergence obtained Compute and print desired L.F. results
STOP

Fig- 3.1 Flow chart for FDLP Algorithm for Unadjusted case using 1δ-1V Scheme.

$$\Delta Q = Q^{sp} - Q^{cal} \tag{3.14}$$

10) Check, if reactive powers at P-Q buses have converged (Max. $\Delta Q \le \varepsilon$). If so, go to step-14, otherwise go to step-11.

11) Advance iteration count by 0.5 ($k = k + 0.5$) and compute vector $[\Delta V]$ from eqn. (3.11).

12) Update the voltage for all P-Q buses using the corrections ΔV obtained in step-11 as

$$V = V + \Delta V \tag{3.15}$$

13) Go to step-5 and repeat the procedure.

14) Check, if max. $\Delta P \le \varepsilon$. If not, then go to step-5 and repeat the proecedure, otherwise go to step-15.

15) Load flow convergence obtained, calculate slack bus power, line flows & line losses.

3.4 Fast Decoupled Load Flow Method in Rectangular Coordinates :

Fast decoupled load flow method [15] in polar coordinates (FDLP) discussed earlier is found to be the most popular method with utilities because of their lesser memory and CPU time requirement. The formulation of a load flow method in rectangular co-ordinates, as observed in Chapter-2, offers faster solution as compared to its formulation in polar co-ordinates, mainly because of the reasons that it does not involve additional computational efforts in solving trigonometric functions. With this in view, development of fast decoupled load flow methods in rectangular co-ordinates (FDLR) appears to be more attractive. Literature survey shows that a little effort has been made in developing FDLR models. The two efforts one by Arumugam [21] and other by Singh et al. [22] incidently result into similar formulation of FDLR model. The development of FDLR model as suggested by them, using two different approaches, one from FDLP model using linear transformation and the other from Newton-Raphson load flow equations are described below.

3.4.1 Derivation of FDLR from FDLP by linear transformation :

The real and imaginary parts of the pth bus voltage in terms of its magnitude and angle are

$$e_p = V_p \text{ Cos } \delta_p \;;\quad f_p = V_p \text{ Sin } \delta_p \qquad (3.16)$$

By taking the exact differentiation of the equation (3.16), we get

$$\begin{bmatrix} \Delta e_p \\ \hline \Delta f_p \end{bmatrix} \quad \begin{bmatrix} -V_p \text{ Sin } \delta_p & \text{Cos } \delta_p \\ \hline V_p \text{ Cos } \delta_p & \text{Sin } \delta_p \end{bmatrix} \begin{bmatrix} \Delta\delta_p \\ \hline \Delta V_p \end{bmatrix} \qquad (3.17)$$

Inverting eqn. (3.17), we obtain

$$\begin{bmatrix} \Delta\delta_p \\ \hline \Delta V_p \end{bmatrix} = \begin{bmatrix} \dfrac{-\text{Sin } \delta_p}{V_p} , & \dfrac{\text{Cos } \delta_p}{V_p} \\ \hline \text{Cos } \delta_p & \text{Sin } \delta_p \end{bmatrix} \begin{bmatrix} \Delta e_p \\ \hline \Delta f_p \end{bmatrix} \qquad (3.18)$$

Applying the transformation (3.18) in eqns. (3.10) and (3.11) in rectangular coordinates the following equations are obtained :

$$\left[\frac{\Delta P}{V}\right] = [B'] \, [A_1' \quad A_2'] \left[\frac{\Delta e}{\Delta f}\right] \qquad (3.19)$$

$$\left[\frac{\Delta Q}{|V|}\right] = [B''] \, [A_1'' \quad A_2''] \left[\frac{\Delta e}{\Delta f}\right] \qquad (3.20)$$

where $[A_1']$, $[A_2']$, $[A_1'']$ and $[A_2'']$ are diagonal matrices with ppth element being given as

$$(A_1')_{pp} = -\frac{\text{Sin } \delta_p}{V_p}$$

$$(A_2')_{pp} = \frac{\text{Cos } \delta_p}{V_p}$$

$$(A_1'')_{pp} = \text{Cos } \delta_p$$

and

$$(A_2'')_{pp} = \text{Sin } \delta_p$$

In the polar version, the voltage magnitude equation do not appear for the P-V buses. Hence, the equations (3.19) and (3.20) in rectangular coordinates have to be augmented by

$$[\Delta V^2] = [A_1''' \quad A_2'''] \left[\frac{\Delta e}{\Delta f}\right] \qquad (3.21)$$

Where, $[A_1''']$ and $[A_2''']$ are diagonal matrices with ppth element given by

$$(A_1''')_{pp} = 2e_p \quad ; \quad (A_2''')_{pp} = 2f_p$$

On combining equations (3.19), (3.20) & (3.21) and making the same assumptions as made in FDLP, namely $V_p \simeq 1.0$, $\delta_p - \delta_q \simeq 0$ etc. and after some manipulations, we get

$$\begin{bmatrix} \Delta P_2 \\ \vdots \\ \Delta P_n \\ \hline \Delta Q_{m+1} \\ \vdots \\ \Delta Q_n \\ \hline \Delta V_2^2 \\ \vdots \\ \Delta V_m^2 \end{bmatrix} = \begin{bmatrix} [\hat{H}] & [\hat{L}] \\ [\hat{M}] & [\hat{N}] \\ [\hat{S}] & [\hat{T}] \end{bmatrix} \begin{bmatrix} \Delta e_2 \\ \vdots \\ \Delta e_n \\ \hline \Delta f_2 \\ \vdots \\ \Delta f_n \end{bmatrix} \qquad (3.22)$$

where,

$$[\hat{H}] = \begin{bmatrix} (-B'_{22}f_2) & \cdots & (-B'_{2m}f_m) & (-B'_{2,m+1}f_{m+1}) & \cdots & (-B'_{2n}f_n) \\ \vdots & & \vdots & \vdots & & \vdots \\ (-B'_{n2}f_2) & \cdots & (-B'_{nm}f_m) & (-B'_{n,m+1}f_{m+1}) & \cdots & (-B'_{nn}f_n) \end{bmatrix}$$

$$[\hat{L}] = \begin{bmatrix} (B'_{22}e_2) & \cdots & (B'_{2m}e_m) & (B'_{2,m+1}e_{m+1}) & \cdots & (B'_{2n}e_n) \\ \vdots & & \vdots & \vdots & & \vdots \\ (B'_{n2}e_2) & \cdots & (B'_{nm}e_m) & (B'_{n,m+1}e_{n+1}) & \cdots & (B'_{nn}e_n) \end{bmatrix}$$

$$[\hat{M}] = \begin{bmatrix} 0 & \cdots & 0 & (B''_{m+1,m+1}e_{m+1}) & \cdots & (B''_{m+1,n}e_n) \\ \vdots & & \vdots & \vdots & & \vdots \\ 0 & \cdots & 0 & (B''_{n,m+1}e_{m+1}) & \cdots & (B''_{nn}e_n) \end{bmatrix}$$

$$[\hat{N}] = \begin{bmatrix} 0 & \cdots & 0 & (B''_{m+1,m+1}f_{m+1}) & \cdots & (B''_{m+1,n}f_n) \\ \vdots & & \vdots & \vdots & & \vdots \\ 0 & \cdots & 0 & (B''_{n,m+1}f_{m+1}) & \cdots & (B''_{nn}f_n) \end{bmatrix}$$

$$[\hat{S}] = \begin{bmatrix} 2e_2 & \cdots & 0 & 0 & \cdots & 0 \\ \vdots & & \vdots & \vdots & & \vdots \\ 0 & \cdots & 2e_m & 0 & \cdots & 0 \end{bmatrix}$$

$$[\hat{T}] = \begin{bmatrix} 2f_2 & \cdots & 0 & 0 & \cdots & 0 \\ \vdots & & \vdots & \vdots & & \vdots \\ 0 & \cdots & 2f_m & 0 & \cdots & 0 \end{bmatrix}$$

In the above derivation, the bus-1 is taken as slack bus, buses 2-m on P-V buses and buses m+1 to n as P-Q buses. To achieve decoupling, the following further assumptions are made :

i) A flat voltage start ($e+jf = 1.0+j0.0$) is used.

ii) The matrices obtained using the flat voltage start are treated as constant at every subsequent iterative step. This avoids the re-calculation and re-triangulation of the Jacobian matrix at each iteration. The algorithm obtained, therefore, utilizes the fixed tangent slopes corresponding to the flat voltage start instead of the varying tangent slopes at each iteration.

With the above assumptions, eqn. (3.22) is reduced to the following set of decoupled equations in rectangular coordinates :

$$\begin{bmatrix} \Delta P_2 \\ \cdot \\ \cdot \\ \Delta P_n \end{bmatrix} = [B'] \begin{bmatrix} \Delta f_2 \\ \cdot \\ \cdot \\ \Delta f_n \end{bmatrix} \qquad (3.23)$$

$$\begin{bmatrix} \Delta Q_{m+1} \\ \cdot \\ \cdot \\ \Delta Q_n \end{bmatrix} = [B''] \begin{bmatrix} \Delta e_{m+1} \\ \cdot \\ \cdot \\ \Delta e_n \end{bmatrix} \qquad (3.24)$$

$$\begin{bmatrix} \Delta V_2^2 \\ \cdot \\ \cdot \\ \Delta V_m^2 \end{bmatrix} = [B'''] \begin{bmatrix} \Delta e_2 \\ \cdot \\ \cdot \\ \Delta e_m \end{bmatrix} \qquad (3.25)$$

where $[B'''] = 2[\hat{I}]$.

Since $[\Delta f]$ and hence $[f]$ are known for the P-V buses from eqn. (3.23), $[e]$ for the P-V buses can be calculated using its specified voltage magnitude from

$$[e^2] = [V^{sp}]^2 - [f^2] \qquad (3.26)$$

Replacing eqn. (3.25) by eqn. (3.26), the final FDLR equations become,

$$[\Delta P] = [B'] \; [\Delta f] \qquad (3.27)$$

$$[\Delta e] = ([V^{sp}]^2 - [f^2])^{1/2} \qquad (3.28)$$

$$[\Delta Q] = [B''] \; [\Delta e] \qquad (3.29)$$

The above equations can also be obtained from Newton-Raphson load flow equations in rectangular coordinates as indicated below.

3.4.2 Derivation of FDLR from Newton-Raphson load flow equations :

With the flat voltage (1.0+j0.0) start at all the buses and also using it for forming the Jacobian in NR load flow equations (2.13), its elements get modified as follows :

$$\frac{\partial P_p}{\partial e_q} = - \frac{\partial Q_p}{\partial f_q} = G_{pq} \qquad (3.30)$$

$$\frac{\partial P_p}{\partial f_q} = \frac{\partial Q_p}{\partial e_q} = - B_{pq} \qquad (3.31)$$

$$\frac{\partial P_p}{\partial e_p} = \hat{a}_p + G_{pp} \qquad (3.32)$$

$$\frac{\partial P_p}{\partial f_p} = \hat{b}_p - B_{pp} \qquad (3.33)$$

$$\frac{\partial Q_p}{\partial e_p} = -\hat{b}_p - B_{pp} \qquad (3.34)$$

$$\frac{\partial Q_p}{\partial f_p} = \hat{a}_p - G_{pp} \qquad (3.35)$$

where,

$$\hat{a}_p = \sum_{q=1}^{n} G_{pq} \qquad (3.36)$$

and

$$\hat{b}_p = \sum_{q=1}^{n} B_{pq} \qquad (3.37)$$

From equations (3.36) and (3.37), we may assume $\hat{a}_p << G_{pp}$ and $\hat{b}_p << B_{pq}$ and hence $\hat{a}_p$ and $\hat{b}_p$ can be neglected in equations (3.32-3.35). Further, neglecting G_{pq} and G_{pp} in the above expressions, the load flow equations reduce to,

$$[\Delta P] = [B_P] \; [\Delta f] \qquad (3.38)$$

$$[\Delta Q] = [B_Q] \; [\Delta e] \qquad (3.39)$$

$$[\Delta V^2] = [B'''] \; [\Delta e] \qquad (3.40)$$

Where, $[B_P]$ and $[B_Q]$ are the elements of $[-B]$ matrix. Incorporating various assumptions of FDLP in forming matrices $[B_P]$ and $[B_Q]$, they get modified to matrices [B'] and [B"] respectively of FDLP model of Stott and Alsac [15]. Replacing $[B_P]$ and $[B_Q]$ by [B'] and [B"] matrices respectively in eqns. (3.38) and (3.39) and using eqn. (3.26) in place of eqn. (3.40), we get the final load flow equations for FDLP model which are nothing but those obtained from FDLP by linear transformation represented by equations (3.27-3.29).

3.4.3 Iterative Scheme for Fast Decoupled Load Flow in Rectangular Coordinates

Equations (3.27-3.29) are solved successively using the most recent values. The best iterative scheme found to be (1f, 1e) scheme, which comprises of one solution for $[\Delta f]$ using equation (3.27) to update [f] for both P-V and P-Q buses followed by one solution for [e] using equation (3.28) for only the P-V buses and finally one solution for $[\Delta e]$ using eqn. (3.29) to update [e] for only the P-Q buses. Iterations are repeated till the real and reactive power mismatches are within a specified convergence tolerance. Major computational steps for solution of load flow problem using FDLR model are given in a flow chart (fig. 3.2) which are summarized as follows :-

1) Read system data including line data, loads at various buses, generation data etc.

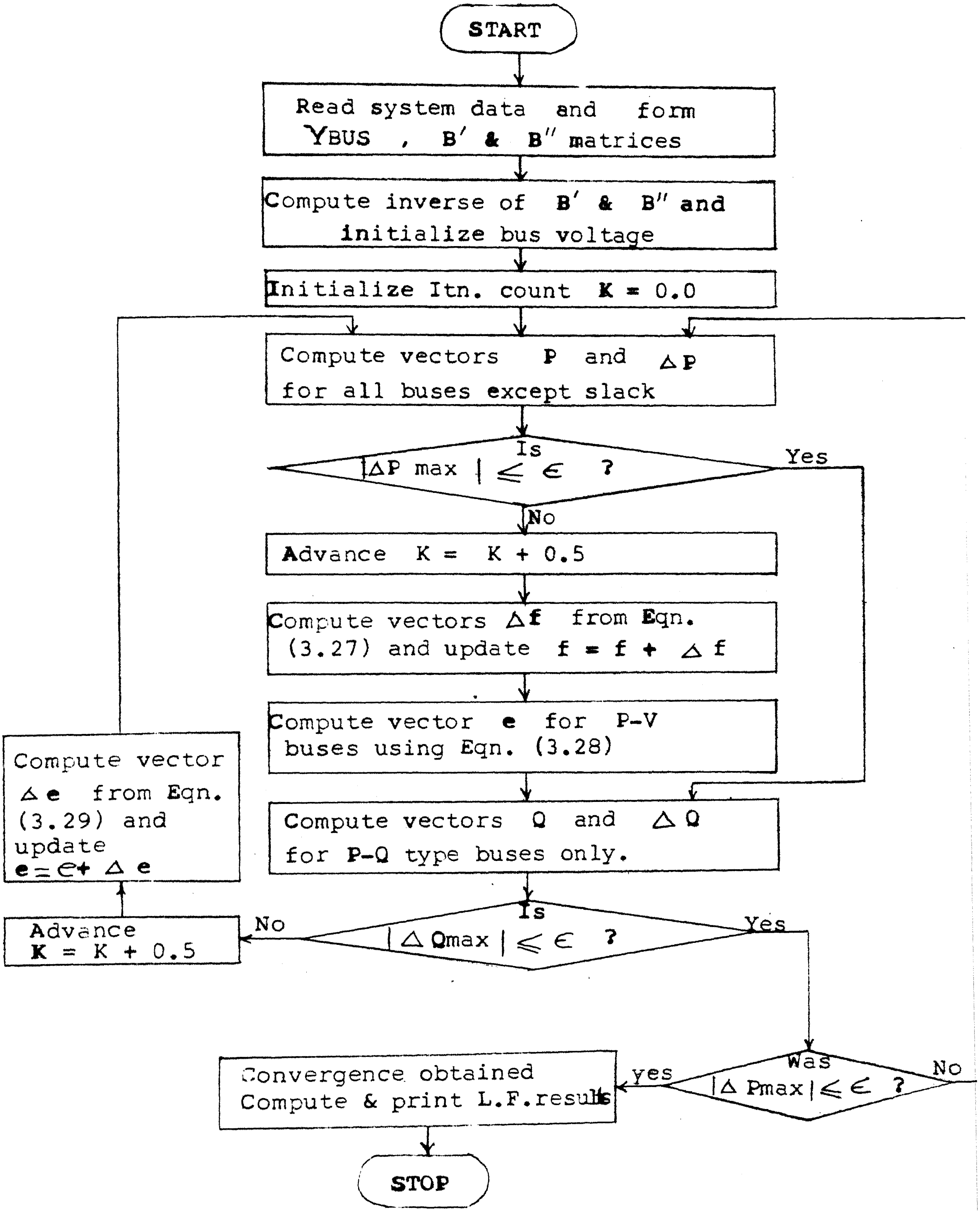
START
Read system data and form YBUS , B′ & B″ matrices
Compute inverse of B′ & B″ and initialize bus voltage
Initialize Itn. count K = 0.0
Compute vectors P and △P for all buses except slack
Is |△P max | ≤ ∈ ?
Yes
No
Advance K = K + 0.5
Compute vectors △f from Eqn. (3.27) and update f = f + △ f
Compute vector e for P-V buses using Eqn. (3.28)
Compute vectors Q and △ Q for P-Q type buses only.
Is | △ Qmax | ≤ ∈ ?
No
Yes
Advance K = K + 0.5
Compute vector △ e from Eqn. (3.29) and update e = e + △ e
Was |△ Pmax | ≤ ∈ ?
No
yes
Convergence obtained Compute & print L.F.results
STOP

Fig- 3.2 Flow chart for FDLR Algorithm for unadjusted case using (1f - 1e) Scheme.

2) Form Y-bus matrix, [B'] and [B"] matrices.

3) Initialize the bus voltage to (1.0+j0.0) p.u.for all P-Q and P-V buses.

4) Set iteration count $k = 0$.

5) Calculate bus real power P and mismatch ΔP for all buses except slack bus using eqn. (3.12)

6) Check if bus real powers have converged (Max. $\Delta P \leq \varepsilon$). If so, go to step-11, otherwise go to step-7.

7) Advance iteration count by 0.5 ($k = k + 0.5$) and solve for Δf using eqn. (3.27).

8) Update f at all buses (both P-V and P-Q buses) using the eqn.

$$f = f + \Delta f \qquad (3.41)$$

9) Calculte e for all P-V buses using eqn. (3.28)

10) Calculate bus reactive power Q and mismatch ΔQ for all P-Q buses using eqn. (3.14).

11) Check, if reactive powers have converged (Max. $\Delta Q \leq \varepsilon$). If so,go to step-16, otherwise go to step-12.

12) Advance iteration count by 0.5 ($k = k + 0.5$) and compute vector Δe using eqn. (3.29).

13) Update e at all P-Q buses using eqn.

$$e = e + \Delta e \qquad (3.42)$$

14) Go to step-5 and repeat the procedure.

15) Check, if max. $\Delta P \leq \varepsilon$. If not, go to step-5 and repeat the proecedure, otherwise go to step-16.

16) Load flow convergence obtained, calculate slack bus power, line flows, line losses etc.

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3.5 New Formulations of Fast Decoupled Load Flow Method in Rectangular Co-ordinates :

Since, the existing FDLR model [21,22] described in earlier section considers all the assumptions of FDLP and in addition, certain further unrealistic simplifications, it is found to offer a convergence pattern inferior to the FDLP model. In fact, the number of iterations taken by FDLR is found to be always more than FDLP. Time superiority of FDLR may be due to less time required in power calculations in rectangular coordinates than in polar coordinates. To overcome the drawback of the above model, two new formulations of FDLR model are developed as below :

3.5.1 New FDLR Model-I (NFDR-I) :

By considering no further assumptions in the model to those already considered in FDLP, for the pth bus, voltage in rectangular coordinates can be written as,

$$e_p = V_p \text{ Cos } \delta_p \tag{3.43}$$

$$f_p = V_p \text{ Sin } \delta_p \tag{3.44}$$

Using exact differentiation, Δe_p and Δf_p can be written as

$$\Delta e_p = - V_p \text{ Sin } \delta_p \, \Delta\delta_p + \text{Cos } \delta_p \, \Delta V_p \tag{3.45}$$

and $$\Delta f_p = V_p \cos \delta_p \, \Delta\delta_p + \sin \delta_p \, \Delta V_p \tag{3.46}$$

Solving these eqns., we obtain

$$\Delta V_p = \cos \delta_p \, \Delta e_p + \sin \delta_p \, \Delta f_p \tag{3.47}$$

and $$\Delta\delta_p = - \frac{\sin \delta_p}{V_p} \Delta e_p + \frac{\cos \delta_p}{V_p} \Delta f_p \tag{3.48}$$

Substituting values of Sin δ_p and Cos δ_p from eqs. (3.43) and (3.44) we get

$$\Delta V_p = \frac{e_p}{V_p} \Delta e_p + \frac{f_p}{V_p} \Delta f_p \tag{3.49}$$

$$\Delta\delta_p = - \frac{f_p}{V_p^2} \Delta e_p + \frac{e_p}{V_p^2} \Delta f_p \tag{3.50}$$

Writing FDLP eqn. for real power mismatch for bus-p, we have

$$\frac{\Delta P_p}{V_p} = \sum_{q=2}^{n} B'_{pq} \, \Delta\delta_q \qquad \text{('1' being the slack bus)}$$

$$= -\sum_{q=2}^{n} B'_{pq} \frac{f_q}{V_q^2} \Delta e_q + \sum_{q=2}^{n} B'_{pq} \frac{e_q}{V_q^2} \Delta f_q$$

or $$\left[\frac{\Delta P_p}{V_p} + \sum_{q=2}^{n} B'_{pq} \frac{f_q}{V_q^2} \Delta e_q \right] = \sum_{q=2}^{n} B'_{pq} \left(\frac{e_q}{V_q^2} \Delta f_q \right) \tag{3.51}$$

Eqn. (3.51) may be written in matrix form as,

$$[\Delta P_p^m] = [B'_{pq}] \, [\Delta f_q^m] \qquad (3.52)$$

Similarly, the FDLP equation for reactive power mismatch at bus-p

i.e. $$\frac{\Delta Q_p}{V_p} = \sum_{q=m+1}^{n} B''_{pq} \, \Delta V_q \qquad \text{(for P-Q buses only)}$$

can be modified by substituting the values of ΔV_q from eqn. (3.49) as :

$$\frac{\Delta Q_p}{V_p} = \sum_{q=m+1}^{n} B''_{pq} \left(\frac{e_q}{V_q} \Delta e_q + \frac{f_q}{V_q} \Delta f_q \right)$$

or $$\left[\frac{\Delta Q_p}{V_p} - \sum_{q=m+1}^{n} B''_{pq} \frac{f_q}{V_q} \Delta f_q \right] = \sum_{q=m+1}^{n} B''_{pq} \frac{e_q}{V_q} \Delta e_q \qquad (3.53)$$

Eqn. (3.53) can be written in matrix form as

$$[\Delta Q_p^m] = [B''_{pq}] \, [\Delta e_q^m] \qquad (3.54)$$

Hence, final set of equations for NFDR-I including voltage mismatch equations for P-V buses can be written as

$$[\Delta P^{m}] = [B'] \; [\Delta f^{m}] \tag{3.55}$$

$$[e] = ([V^{sp}]^{2} - [f^{2}])^{1/2} \tag{3.56}$$

$$[\Delta Q^{m}] = [B''] \; [\Delta e^{m}] \tag{3.57}$$

Where, the superscript m stands for modified values given by

$$\Delta P_{p}^{m} = \frac{\Delta P_{p}}{V_{p}} + f_{1}(\Delta e) \tag{3.58}$$

$$\Delta Q_{p}^{m} = \frac{\Delta Q_{p}}{V_{p}} + f_{2}(\Delta f) \tag{3.59}$$

$$\Delta f_{q}^{m} = \frac{e_{q}}{V_{q}^{2}} \Delta f_{q} \tag{3.60}$$

$$\Delta e_{q}^{m} = \frac{e_{q}}{V_{q}} \Delta e_{q} \tag{3.61}$$

Here, $f_1(\Delta e)$ and $f_2(\Delta f)$ denote functions of Δe's and Δf's respectively, given as

$$f_{1}(\Delta e) = \sum_{q=2}^{n} B'_{pq} \frac{f_{q}}{V_{q}^{2}} \Delta e_{q}$$

and

$$f_{2}(\Delta f) = -\sum_{q=m+1}^{n} B''_{pq} \frac{f_{q}}{V_{q}} \Delta f_{q}$$

During the first half iteration, Δe is not available, therefore, ΔP^m is taken as $\Delta P/V$, and in subsequent iterations when $[\Delta e]$ and $[\Delta f]$ assume certain values, these are used to compute $[\Delta P^m]$ and $[\Delta Q^m]$. Eqns. (3.55-3.57) are solved successively using the most recent values. The best iteration strategy is termed as the (1f, 1e) scheme, which comprises of one solution for $[\Delta f]$ to update $[f]$ for both P-V & P-Q buses, one solution for $[e]$ using eqn. (3.56) for only P-V buses and then one solution for $[\Delta e]$ to update $[e]$ for only the P-Q buses. Iterations are repeated until the real and reactive power mismatches are within a specified convergence tolerance. Major computational steps for the proposed model of FDLR is presented in a flow chart (Fig. 3.3) which is summarized as following :

1) Read system data including line data, loads at P-Q buses, generator data etc.
2) Form Y-bus matrix, $[B']$ and $[B'']$ matrices.
3) Initialize the bus voltage to (1+j0) p.u. for all P-Q and P-V buses.
4) Set iteration count $k = 0$.
5) Calculate $[\Delta P^m]$ for all buses except slack bus using eqn. (3.12).
6) Test for convergence of bus real powers (max. $\Delta P \leq \varepsilon$). If convergence obtained, go to step-11, otherwise go to step-7.
7) Advance iteration count by 0.5 ($k = k + 0.5$) and solve for Δf using eqn. (3.60).
8) Update f at all buses (both P-Q and P-V buses) using the eqn.

$$f = f + \Delta f$$

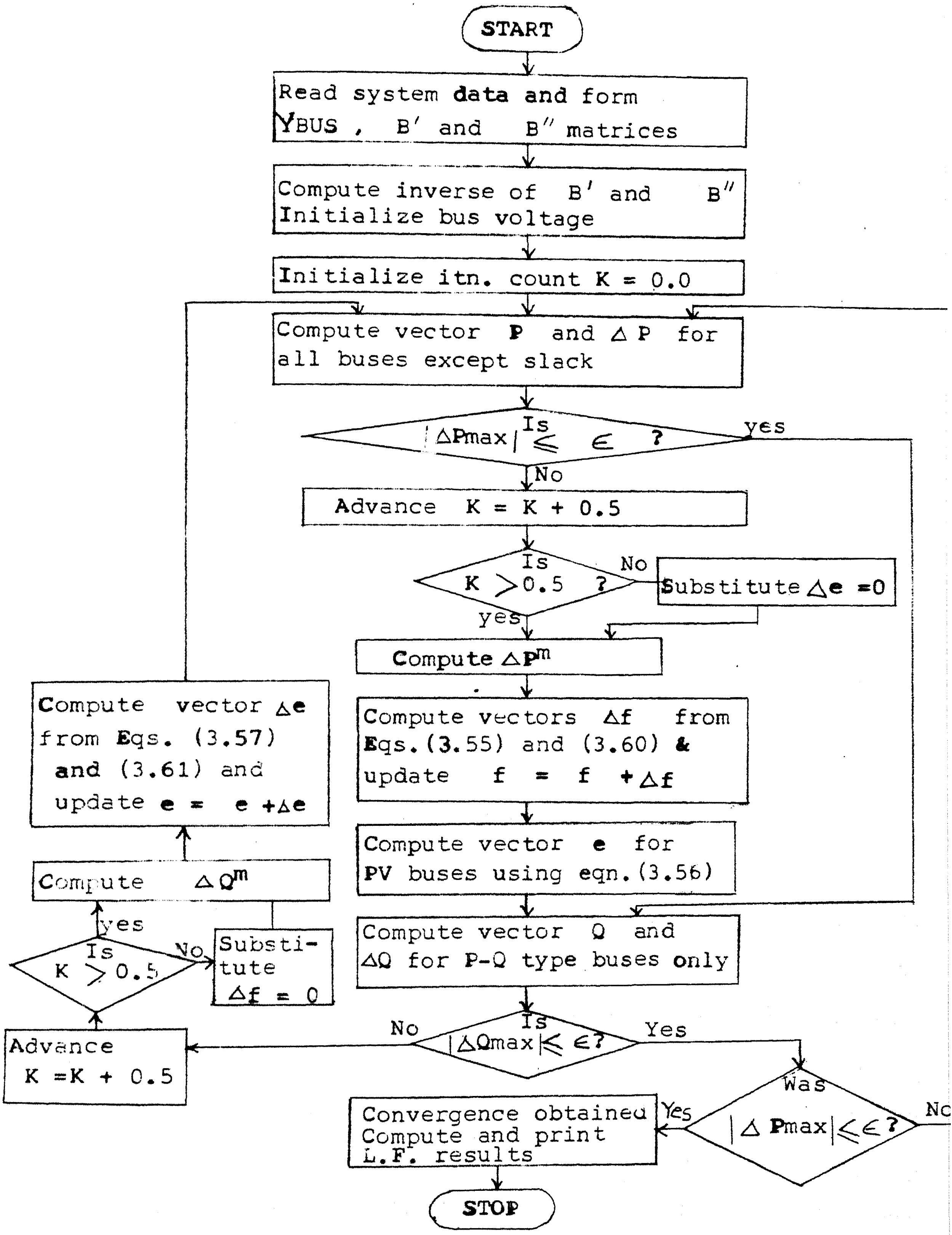
START
Read system data and form YBUS, B′ and B″ matrices
Compute inverse of B′ and B″ Initialize bus voltage
Initialize itn. count K = 0.0
Compute vector P and △P for all buses except slack
Is |△Pmax| ⩽ ∈ ?
yes
No
Advance K = K + 0.5
Is K > 0.5 ?
No
Substitute △e = 0
yes
Compute △P^m
Compute vectors △f from Eqs. (3.55) and (3.60) & update f = f + △f
Compute vector e for PV buses using eqn. (3.56)
Compute vector Q and △Q for P-Q type buses only
Is |△Qmax| ⩽ ∈?
No
Yes
Advance K = K + 0.5
Is K > 0.5
yes
No
Substitute △f = 0
Compute △Q^m
Compute vector △e from Eqs. (3.57) and (3.61) and update e = e + △e
Was |△Pmax| ⩽ ∈?
Yes
No
Convergence obtained Compute and print L.F. results
STOP

Fig- 3.3 Flow chart for NFDR Algorithms for unadjusted case using 1f - 1e Scheme.

9) Calculate e for all P-V buses using eqn. (3.56)

10) Calculate ΔQ^m for all P-Q buses using eqn. (3.57).

11) Test for convergence of bus reactive powers (Max. $\Delta Q \le \varepsilon$). If convergence obtained, go to step-16, otherwise go to step-12.

12) Advance iteration count by 0.5 ($k = k + 0.5$) and compute Δe using eqn. (3.61).

13) Update e at all P-Q buses using eqn.

$$e = e + \Delta e$$

14) Go to step-5.

15) Check, if max. $\Delta P \le \varepsilon$. If not go to step-5, otherwise to go step -16.

16) Convergence obtained. Calculate slack bus power, line flows, line losses etc.

3.5.2 Modified version of New FDLR Model-I (NFDR-IM)

In NFDR-I model described in section 3.5.1, [B'] and [B"] matrices are formed using all the assumptions made by Stott and Alsac in their FDLP [15] model. Van Amerongen [24] in his work has suggested certain modifications in usual FDLP model which results into better convergence pattern especially for solving the ill-conditioned systems. The modifications suggested by him is mainly on considering a different combination of additional assumptions other than made by Stott & Alsac [15] in forming [B'] and [B"] matrices. Hence a modified version of New FDLR model was also tried out incorporating the changes suggested by Van Amerongen [24] while forming [B'] and [B"] matrices. Various modifications include :

a) Line series resistance should be neglected in forming [B"] matrix instead of [B'] matrix used in usual FDLP model [15].

b) [B"] matrix is formed considering double the nominal value of line shunt capacitances.

The iterative scheme for solving load flow problem using the modified version (NFDR-IM) is exactly same as that for NFDR-I scheme described in section 3.5.1.

3.5.3 New FDLR Model-II (NFDR-II) :

A different version of FDLR was developed which is directly derived from Newton-Raphson load flow equations in rectangular coordinates using the only approximation that, the initial value of voltage at all buses are assumed to be $1\angle 0^\circ$ for calculation of elements of Jacobian. The elements of Jacobian will be as follows :

$$(J_1)_{pp} = \sum_{q=1}^{n} G_{pq} + G_{pp} = G_{pp} \tag{3.62}$$

$$(J_1)_{pq} = G_{pq} \tag{3.63}$$

$$(J_2)_{pp} = B_{pp} - \sum_{q=1}^{n} B_{pq} = B_{pp} - B_{shp} \tag{3.64}$$

$$(J_2)_{pq} = B_{pq} \tag{3.65}$$

$$(J_3)_{pp} = 2e_p \tag{3.66}$$

$$(J_3)_{pq} = 0 \tag{3.67}$$

$$(J_4)_{pp} = 2f_p \tag{3.68}$$

$$(j_4)_{pq} = 0 \tag{3.69}$$

$$(J_5)_{pp} = B_{pp} + \sum_{q=1}^{n} B_{pq} = B_{pp} + B_{shp} \tag{3.70}$$

$$(J_5)_{pq} = B_{pq} \tag{3.71}$$

$$(J_6)_{pp} = \sum_{q=1}^{n} G_{pq} - G_{pp} = - G_{pp} \tag{3.72}$$

$$(J_6)_{pq} = - G_{pq} \tag{3.73}$$

Using above, the P-f eqn. (for P-Q and P-V buses) will be

$$\Delta P_p = \sum_{q=2}^{n} G_{pq} \Delta e_q + (B_{pp} - B_{shp}) \Delta f_p + \sum_{\substack{q=2 \\ \neq p}}^{n} B_{pq} \Delta f_q$$

or
$$[\Delta P_p - \sum_{q=2}^{n} G_{pq} \Delta e_q] = (B_{pp} - B_{shp}) \Delta f_p + \sum_{\substack{q=2 \\ \neq p}}^{n} B_{pq} \Delta f_q$$

or $$[\Delta P^m] = [B'_r]\,[\Delta f] \qquad (3.74)$$

where, the diagonal elements of $[B'_r] = B_{pp} - B_{shp}$ & the off-diagonal elements of $[B'_r] = B_{pq}$.

For the voltage update equation for P-V buses, we use

$$[e] = ([V^{sp}]^2 - [f^2])^{1/2} \qquad (3.75)$$

Similarly, Q-e eqn. for P-Q buses can be derived as,

$$\Delta Q_p = (B_{pp} + B_{shp})\,\Delta e_p + \sum_{\substack{q=2\\ \neq p}}^{n} B_{pq}\,\Delta e_q - \sum_{q=2}^{n} G_{pq}\,\Delta f_q$$

or $$[\Delta Q_p + \sum_{q=2}^{n} G_{pq}\,\Delta f_q] = (B_{pp} + B_{shp})\Delta e_p + \sum_{\substack{q=2\\ \neq p}}^{n} B_{pq}\,\Delta e_q$$

or $$[\Delta Q^m] = [B''_r]\,[\Delta e] \qquad (3.76)$$

where, the diagonal elements of $B''_r = B_{pp} + B_{shp}$ and the off-diagonal elements of $B''_r = B_{pq}$.

B_{shp} is the total additional shunts at bus p. Thus the final set of eqns. for NFDR-II model will be

$$[\Delta P^m] = [B'_r]\ \ [\Delta f] \qquad (3.77)$$

$$[e] = ([V^{sp}]^2 - [f^2])^{1/2} \qquad (3.78)$$

$$[\Delta Q^m] = [B_r''] \; [\Delta e] \qquad (3.79)$$

where,

$$\Delta P^m = \Delta P + \text{function of } (\Delta e)$$

$$\Delta Q^m = \Delta Q + \text{function of } (\Delta f)$$

During the first half iteration, $[\Delta e]$ is not available, therefore, ΔP^m is taken as ΔP, but in subsequent iterations when $[\Delta e]$ and $[\Delta f]$ assume certain values, these are used to compute $[\Delta P^m]$ and $[\Delta Q^m]$. For load flow solution(1f, 1e) scheme described for NFDR-I model in section 3.5.1 is also used for the proposed NFDR-II model.Iterations are repeated until the real and reactive power mismatches are within a specified convergence tolerance.

3.6 Sample System Studies

The FDLP, FDLR, NFDR-I, NFDR-IM and NFDR-II models discussed in previous sections have been tested by solving the load flows for the following power system examples on DEC-1090 system.

1. IEEE 14 bus test system.
2. IEEE 30 bus test system.

The specifications of the above systems are given in Appendices - A & B.

TABLE - 3.1

Comparison of Various Fast Decoupled Load Flow Models
(Base Case)

Method	IEEE - 14 BUS		IEEE - 30 BUS	
	No. of Iterations	CPU Time (seconds)	No. of Iterations	CPU Time (seconds)
FDLP	4.0	0.392	3.5	1.861
FDLR	5.5	0.419	6.5	2.082
NFDR-I	11.5	0.615	14.5	3.081
NFDR-IM	12.5	0.628	17.5	3.512
NFDR-II	22.5	0.856	33.0	4.689

TABLE - 3.2

Effect of Large Line R/X Ratio on Convergence (Type-a Simulation)

A) IEEE - 14 Bus System :

Ill-conditioning case (1+α)R + jX	Number of Iterations				
	FDLP	FDLR	NFDR-I	NFDR-IM	NFDR-II
1.5 R + jX	5.5	8.5	13.0	13.5	Div.
2.0 R + jX	8.0	13.0	14.0	14.5	Div.
2.5 R + jX	11.0	28.5	16.0	16.5	Div.
3.0 R + jX	14.5	39.0	19.0	20.5	Div.
3.5 R + jX	21.0	Osc.	27.0	28.5	Div.
4.0 R + jX	36.5	Div.	135.0	Div.	Div.

Osc. - Oscillating
Div. - Diverged

B) IEEE - 30 Bus System :

Ill-conditioning case (1+α)R + jX	Number of Iterations				
	FDLP	FDLR	NFDR-I	NFDR-IM	NFDR-II
1.5 R + jX	6.0	11.5	16.5	19.5	Div.
2.0 R + jX	8.5	16.0	18.0	24.5	Div.
2.5 R + jX	12.0	42.0	29.0	38.5	Div.
3.0 R + jX	17.0	Osc.	81.0	Div.	Div.
3.5 R + jX	26.5	Div.	Div.	Div.	Div.
4.0 R + jX	76.0	Div.	Div.	Div.	Div.

TABLE - 3.3

Effect of Large Line R/X Ratio on Convergence (Type-b Simulation)

A) IEEE - 14 Bus System :

Ill-conditioning case $R + j(1-\beta)X$	Number of Iterations				
	FDLP	FDLR	NFDR-I	NFDR-IM	NFDR-II
R + j0.75X	4.5	7.5	9.5	9.5	Div.
R + j0.50X	7.0	8.0	9.0	8.5	Div.
R + j0.25X	17.0	18.5	18.5	9.0	Div.
R + j0.20X	23.5	23.5	26.0	10.5	Div.
R + j0.10X	88.0	Osc.	94.5	15.0	Div.

B) IEEE - 30 Bus System :

Ill-conditioning case $R + j(1-\beta)X$	Number of Iterations				
	FDLP	FDLR	NFDR-I	NFDR-IM	NFDR-II
R + j0.75X	5.0	7.0	11.5	11.5	Div.
R + j0.50X	7.0	9.0	9.5	8.5	Div.
R + j0.25X	17.0	19.0	14.5	8.0	Div.
R + j0.20X	24.5	27.5	20.0	9.0	Div.
R + j0.10X	Osc.	Osc.	73.0	14.0	Div.

3.7 Discussions and Conclusions

In this chapter, the fast decoupled load flow methods in polar and in rectangular coordinates are presented. Three new formulations for FDLR are also suggested. All these methods have been tested on IEEE - 14 Bus and 30 Bus test systems both for the base case as well as ill-conditioned situations simulated for large R/X ratio of lines.

All the five methods (FDLP, FDLR, NFDR-I, NFDR-IM and NFDR-II) utilize constant Jacobian's of similar size and thus have identical memory requirements. All these methods exhibit a geometric convergence pattern.

Based on the results shown in Tables 3.1 to 3.3, the relative computational performance of different methods are summarized below :-

1. From the CPU time tabulated in the present chapter and Chapter-2, it is clearly evident that all the five versions of fast decoupled load flow methods are faster than Newton-Raphson methods in polar as well as in rectangular coordinates.
2. Although, FDLR takes more number of iterations for convergence as compared to FDLP, the total CPU time is comparable with FDLP model.
3. The computational time required per iteration of FDLR is less than the corresponding iteration time for FDLP model.

4. The proposed NFDR-I model though takes more number of iterations for base case, as compared to existing FDLR, it has better convergence characteristics especially for ill-conditioned cases simulated by increasing the resistance of lines.

5. The proposed NFDR-II model takes maximum number of iterations for base case and also diverges for ill-conditioned cases. Hence it is not recommended for load flow solution.

6. The proposed modified version NFDR-IM model takes least number of iterations for ill-conditoned cases (simulated by decreasing the line reactances) as compared to all other versions of fast decoupled load flow models.

CHAPTER - IV

CONCLUSION

The works carried out in this thesis have been aimed at comparing different existing load flow methods, viz. Newton-Raphson method & fast decoupled load flow methods in polar and in rectangular co-ordinates as well as developing improved solution techniques for power system load flow studies. Three new formulations of fast decoupled load flow methods in rectangular co-ordinates have been presented in this thesis. The importance of any load flow solution depends largely upon its merits regarding reliability, convergence characteristics, solution time and memory requirements. The above methods differ, mostly, in their memory and computation time requirements. Keeping this in view a comparative study of the aforementioned methods has been made.

The potential of the existing NR and FDLF methods in polar and rectangular co-ordinates and new algorithms of FDLF methods in rectangular co-ordinates have been tested on IEEE-14 bus and 30 bus systems both for well behaved and ill-conditioned cases. From the comparison of the test results of all these methods presented in Chapter 2 and 3, it is concluded that,

(1) Newton-Raphson load flow methods in polar and rectangular co-ordinates are found to be highly reliable for solving well behaved and ill-conditioned systems. The number of iterations taken by these methods are almost independent of system size and kind.

(2) Between the two Newton-Raphson methods, the polar version (NRP) requires less memory than the rectangular version(NRR) whereas the formulation in rectangular version is found to be slightly faster than its polar counterpart.

(3) Fast decoupled load flow method in polar co-ordinates and all its four versions in rectangular co-ordinates are found to be much faster than Newton-Raphson methods in polar as well as in rectangular co-ordinates and also have lesser memory requirements as compared to the two NR methods.

(4) For base case studies although the fast decoupled load flow methods in rectangular co-ordinates (FDLR) take more number of iterations as compared to its formulation in polar co-ordinates (FDLP), the total CPU time is comparable with the FDLP model. In fact the CPU time required per iteration by FDLR model is less than that required by FDLP model.

(5) Amongst the three new formulations of fast decoupled load flow models in rectangular co-ordinates tried out in Chapter 3, NFDR-I and NFDR-IM version are clearly superior to the existing FDLR model specially for solving ill-conditioned systems. Amongst the two, NFDR-IM model shows better convergence pattern which is even superior to FDLP model in certain situations.

Studies carried out in this thesis on fast decoupled load flow methods were restricted to unadjusted cases without considering the reactive power limits of generators etc. In fact, the main emphasis was to present a comparative study of relative performances of various existing and new load flow models.

However, a practical load flow program should incorporate various system constraints such as generator reactive power limits, limits on transformer tappings, voltage limits at load buses etc. Efficient modelling of these constraints without hampering the constant Jacobian feature of the fast deoupled load flow methods has been an area of research till recent past. Hence, the present work may be extended in future to incorporate this important feature in various fast decoupled load flow programs, which would further enhance its utility.

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APPENDIX - A

DATA FOR IEEE-14 BUS TEST SYSTEM (AT 100 MVA BASE)

The IEEE-14 Bus system is shown in fig. A. The system data is taken from ref. [9] and buses renumbered. The data is compiled in the following manner :

1) Bus data

2) Line data

3) Transformer data

4) Shunt capacitor data

5) Voltage controlled or P-V bus data.

A-1 Bus Data

Bus No.	Generation		Load	
	MW	MVAR	MW	MVAR
1	0.0	0.0	0.0	0.0
2	40.0	0.0	21.7	12.7
3	0.0	0.0	94.2	19.0
4	0.0	0.0	11.2	7.5
5	0.0	0.0	0.0	0.0
6	0.0	0.0	47.8	-3.9
7	0.0	0.0	0.0	0.0
8	0.0	0.0	7.6	1.6
9	0.0	0.0	29.5	16.6
10	0.0	0.0	9.0	5.8
11	0.0	0.0	3.5	1.8
12	0.0	0.0	6.1	1.6
13	0.0	0.0	13.5	5.8
14	0.0	0.0	14.9	5.0

A-2 Line Data

Line No.	Buses From	Buses To	Line Impedance R in p.u.	Line Impedance X in p.u.	Half Line Charging susceptance (p.u)
1	1	2	0.01938	0.05917	0.0264
2	1	8	0.05403	0.22304	0.0246
3	2	3	0.04699	0.19797	0.0219
4	2	6	0.05811	0.17632	0.0187
5	2	8	0.05695	0.17388	0.0700
6	3	6	0.06701	0.17103	0.0173
7	4	11	0.09498	0.19890	0.0
8	4	12	0.12291	0.25581	0.0
9	4	13	0.06615	0.13027	0.0
10	6	7	0.0	0.20912	0.0
11	6	8	0.01335	0.04211	0.0064
12	6	9	0.0	0.55618	0.0
13	7	5	0.0	0.17615	0.0
14	7	9	0.0	0.11001	0.0
15	8	4	0.0	0.25202	0.0
16	9	10	0.03181	0.08450	0.0
17	9	14	0.12711	0.27038	0.0
18	10	11	0.08205	0.19207	0.0
19	12	13	0.22092	0.19988	0.0
20	13	14	0.17093	0.34802	0.0

A-3 Transformer Data

Transformer	Buses From	Buses To	Tap setting
1	6	7	0.978
2	6	9	0.969
3	8	4	0.932

A-4 Shunt Capacitor Data

Bus No.	Susceptance p.u.
9	0.190

A-5 Voltage-Controlled Bus Data (P-V buses)

Bus No.	Voltage magnitude p.u.	Reactive Power Limits Minimum MVAR	 Maximum MVAR
2	1.045	− 40.0	50.0
3	1.010	0.0	0.0
4	1.070	− 6.0	24.0
5	1.090	− 6.0	24.0

Slack bus voltage = $1.06\underline{/0^0}$

APPENDIX - B

DATA FOR IEEE-30 BUS TEST SYSTEM (AT 100 MVA BASE)

B-1 Bus Data

Bus No.	Generation		Load	
	MW	MVAR	MW	MVAR
1	0.0	0.0	0.0	0.0
2	40.0	0.0	21.7	12.7
3	0.0	0.0	30.0	30.0
4	0.0	0.0	0.0	0.0
5	0.0	0.0	94.2	19.0
6	0.0	0.0	0.0	0.0
7	0.0	0.0	22.8	10.9
8	0.0	0.0	2.4	1.2
9	0.0	0.0	0.0	0.0
10	0.0	0.0	5.8	2.0
11	0.0	0.0	7.6	1.6
12	0.0	0.0	11.2	7.5
13	0.0	0.0	0.0	0.0
14	0.0	0.0	6.2	1.6
15	0.0	0.0	8.2	2.5
16	0.0	0.0	3.5	1.8
17	0.0	0.0	9.0	5.8
18	0.0	0.0	3.2	0.9
19	0.0	0.0	9.5	3.4
20	0.0	0.0	2.2	0.7
21	0.0	0.0	17.5	11.2
22	0.0	0.0	0.0	0.0
23	0.0	0.0	3.2	1.6
24	0.0	0.0	8.7	6.7
25	0.0	0.0	0.0	0.0
26	0.0	0.0	3.5	2.3
27	0.0	0.0	0.0	0.0
28	0.0	0.0	0.0	0.0
29	0.0	0.0	2.4	0.9
30	0.0	0.0	10.6	1.9

B-2 Line Data

Line No.	Buses From	 To	Line Impedance R in p.u.	 X in p.u.	Half Line Charging susceptance (p.u)
1	1	2	0.0192	0.0575	0.0264
2	1	8	0.0452	0.1852	0.0204
3	2	11	0.0570	0.1737	0.0184
4	8	11	0.0132	0.0379	0.0042
5	2	5	0.0472	0.1983	0.0209
6	2	13	0.0581	0.1763	0.0187
7	11	13	0.0119	0.0414	0.0045
8	5	7	0.0460	0.1160	0.0102
9	13	7	0.0267	0.0820	0.0085
10	13	3	0.0120	0.0420	0.0045
11	13	9	0.0	0.2080	0.0
12	13	10	0.0	0.5560	0.0
13	9	4	0.0	0.2080	0.0
14	9	10	0.0	0.1100	0.0
15	11	12	0.0	0.2560	0.0
16	12	6	0.0	0.1400	0.0
17	12	14	0.1231	0.2559	0.0
18	12	15	0.0662	0.1304	0.0
19	12	16	0.0945	0.1987	0.0
20	14	15	0.2210	0.1997	0.0
21	16	17	0.0824	0.1923	0.0
22	15	18	0.1070	0.2185	0.0
23	18	19	0.0639	0.1292	0.0
24	19	20	0.0340	0.0680	0.0
25	10	20	0.0936	0.2090	0.0
26	10	17	0.0324	0.0845	0.0
27	10	21	0.0348	0.0749	0.0
28	10	22	0.0727	0.1499	0.0
29	21	22	0.0116	0.0236	0.0
30	15	23	0.1000	0.2020	0.0
31	22	24	0.1150	0.1790	0.0
32	23	24	0.1320	0.2700	0.0
33	24	25	0.1885	0.3292	0.0
34	25	26	0.2544	0.3800	0.0
35	25	27	0.1093	0.2087	0.0
36	28	27	0.0	0.3960	0.0
37	27	29	0.2198	0.4153	0.0
38	27	30	0.3202	0.6027	0.0
39	29	30	0.2399	0.4533	0.0
40	3	28	0.0636	0.2000	0.0214
41	13	28	0.0169	0.0599	0.0065

B-3 Transformer Data

Transformer	Buses From	 To	Tap setting
1	11	12	0.932
2	13	9	0.978
3	13	10	0.969
4	28	27	0.968

B-4 Shunt Capacitor Data

Bus No.	Susceptance p.u.
10	0.190
24	0.043

B-5 Voltage-Controlled Bus Data (P-V buses)

Bus No.	Voltage magnitude p.u.	Reactive Power Limits Minimum MVAR	 Maximum MVAR
2	1.045	- 40.0	50.0
3	1.010	- 10.0	40.0
4	1.082	- 6.0	24.0
5	1.010	- 40.0	40.0
6	1.073	- 6.0	24.0

Slack bus voltage = $1.06\angle 0^{\circ}$

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